An Assessment of a Hydrogen Cities Concept Applied to a Representative Community

Final Report

Prepared for DOE/NETL

Prepared under CTC Subcontract 030400101

July 14, 2004

TIAX LLC
Acorn Park
Cambridge, Massachusetts
02140-2390

Reference: D0242

Agenda

- Purpose and Scope
- Description of Southpointe
- SOFC Technology Description
- Analytical Approach
- Waste-Heat-Utilization Possibilities
- Integration with Hydrogen Production
- Conclusions and Recommendations
- Appendices

Agenda

Purpose and Scope

Description of Southpointe

SOFC Technology Description

Analytical Approach

Waste-Heat-Utilization Possibilities

Integration with Hydrogen Production

Conclusions and Recommendations

Appendices

The objective of this assignment was to assess the potential benefits of SECA SOFC technology when used within a community energy system.

Potential Benefits

- Reduction in energy costs
- Reduction in primary energy use
- Reductions in emissions
- Reduced requirements for electric grid infrastructure
- Enhanced power quality/reliability
- Options for efficient local generation of Hydrogen

These benefits are enhanced in a *new* community due to the additional flexibility in system placement and up-front integration with utility planning.

Under this Phase I effort, we analyzed two DG configurations serving a representative community (the Southpointe development south of Pittsburgh, PA).

- Analyzed performance and economics of SOFC-based DG plant configurations:
  - Simple-cycle SOFC
  - SOFC and gas turbine hybrid
- Identified siting issues
- Identified uses of waste heat
- Identified strategies for utilizing SOFC technology to increase efficiency and lower cost of local hydrogen generation

We conducted this analysis consistent with the "Quality Guidelines for Energy System Studies", 9/30/03 Draft, prepared by the Office of Systems and Quality Support.

Agenda

- Purpose and Scope
- **Description of Southpointe**
- SOFC Technology Description
- Analytical Approach
- Waste-Heat-Utilization Possibilities
- Integration with Hydrogen Production
- Conclusions and Recommendations
- Appendices

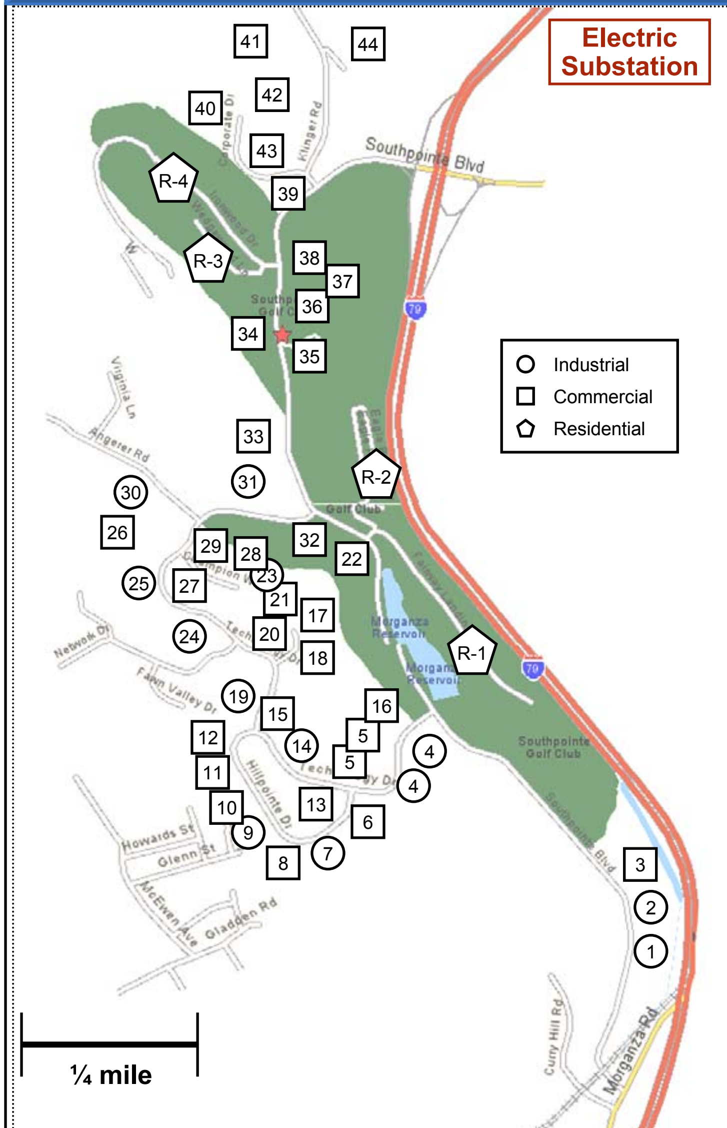
NETL selected Southpointe, a largely commercial and industrial development near Canonsburg, Pennsylvania, as an example community for initial analysis.

Summary Data (for 2003)[1]

Daytime Population:	4200 (estimated)
Summer Peak Power:	12.4 MW
Winter Peak Power:	7.6 MW
Average Power:	5.2 MW
Electric Utility:	Allegheny
Gas Utility:	Columbia Gas

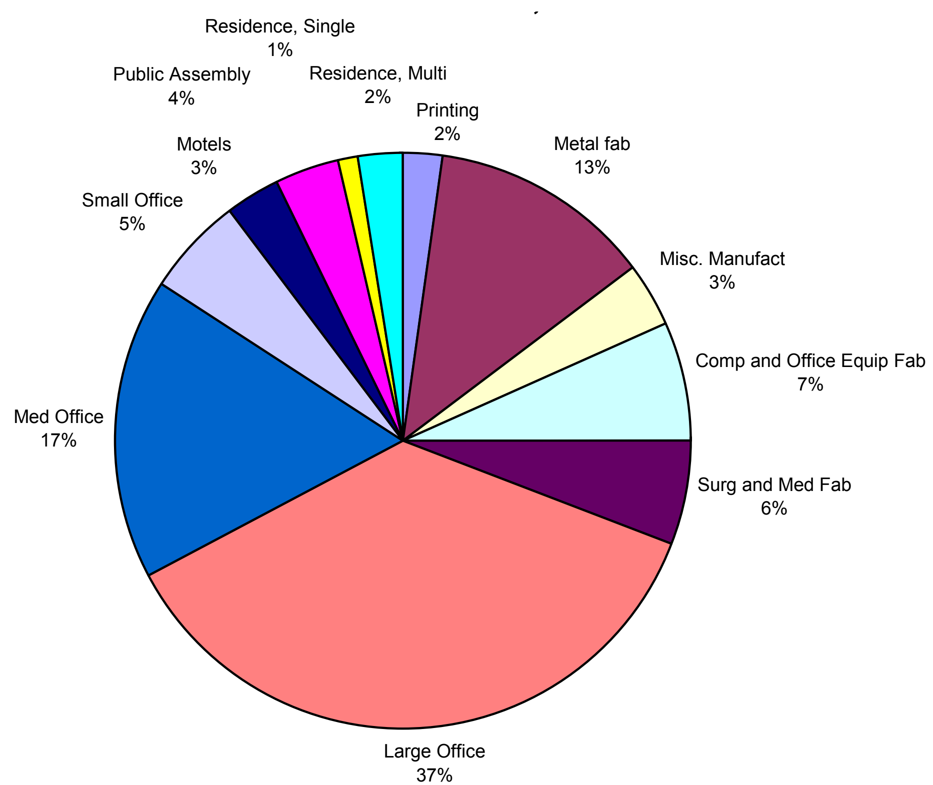
1 Community layout based on information received March 25, 2004. Load profiles are based on information received February 6, 2004. There are minor differences in the two sources, presumably due to actual changes in the community. Population is based on the sum of employment numbers and an estimate of residents from the number of housing units.

Community Layout[1]



59% of Southpointe's electric consumption is in office buildings[1].

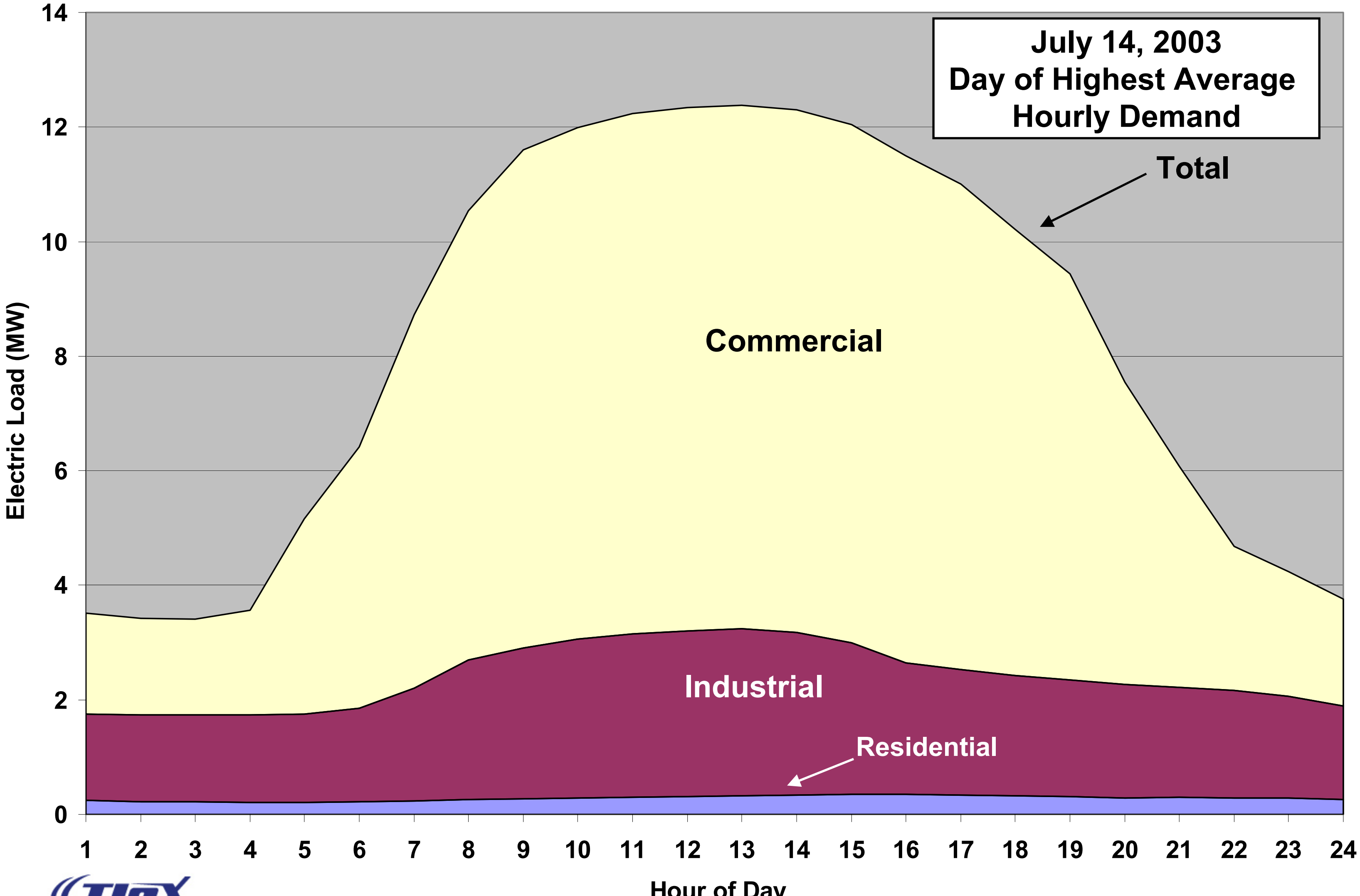
Breakdown of Southpointe Annual Electricity Usage for 2003
Total: 45,653 MWh



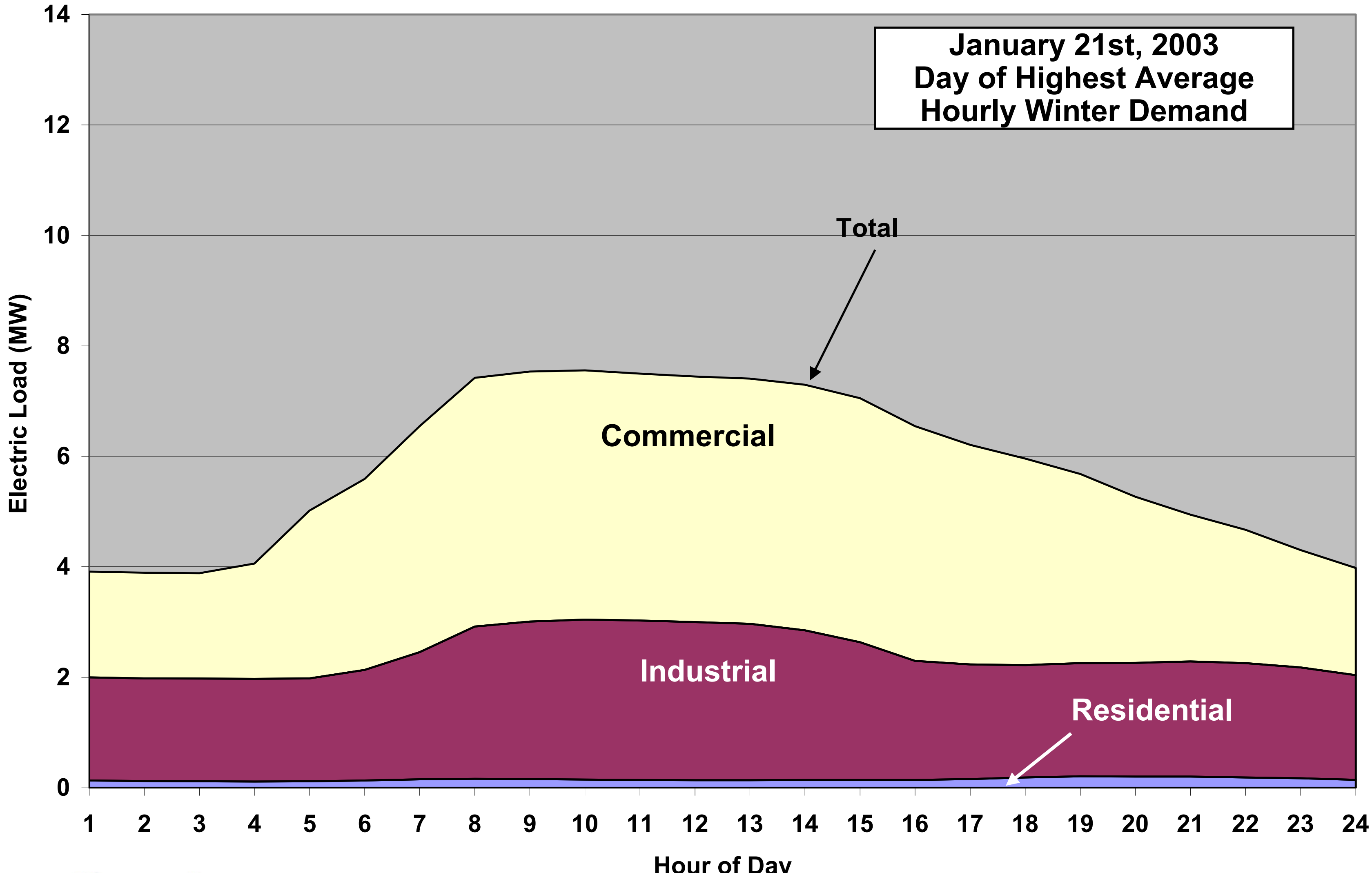
3% Residential
66% Commercial
31% Industrial

[1] Further load-profile details included in Appendix A

Commercial office buildings drive peak-load requirements for the community.



Peak electric demand drops from 12.4 MW in summer to 7.6 MW in winter.

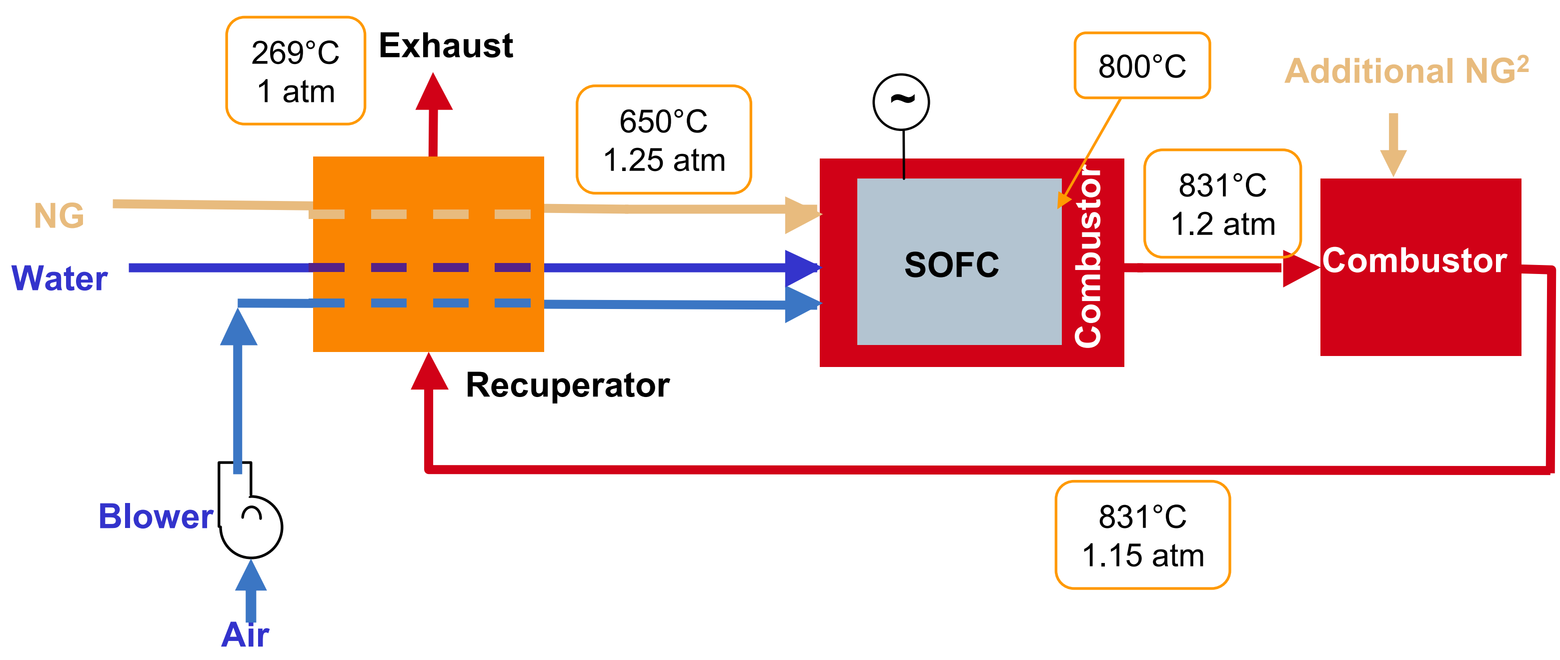


Agenda

- Purpose and Scope
- Description of Southpointe
- **SOFC Technology Description**
- Analytical Approach
- Waste-Heat-Utilization Possibilities
- Integration with Hydrogen Production
- Conclusions and Recommendations
- Appendices

The simple-cycle plant utilizes the system configuration developed under the 250 kW SECA study, which operates at near atmospheric pressure.

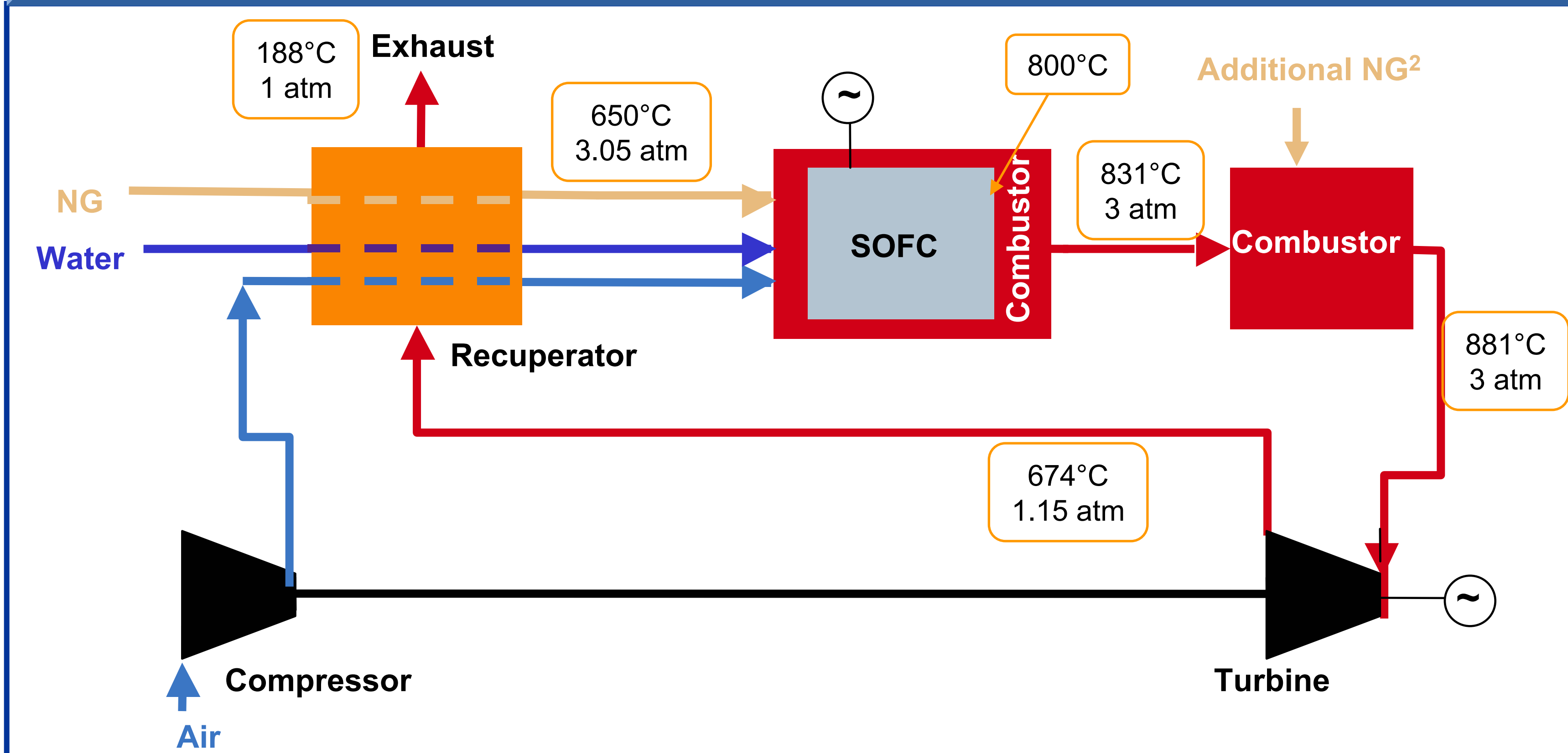
Simple-Cycle SOFC System Configuration[1]



[1]See Appendix B for further details on system configuration and tie-in to electric grid. From: Scale-Up of 5-kW SECA Modules to a 250-kW System; TIAX LLC; Ref 74313; June 10, 2002.
[2]Additional firing needed only for start up and some other transients.

The hybrid plant utilizes the system configuration developed under the MW-Level SECA study, which operates at 3 Atm.

SOFC-GT Hybrid System Configuration[1]



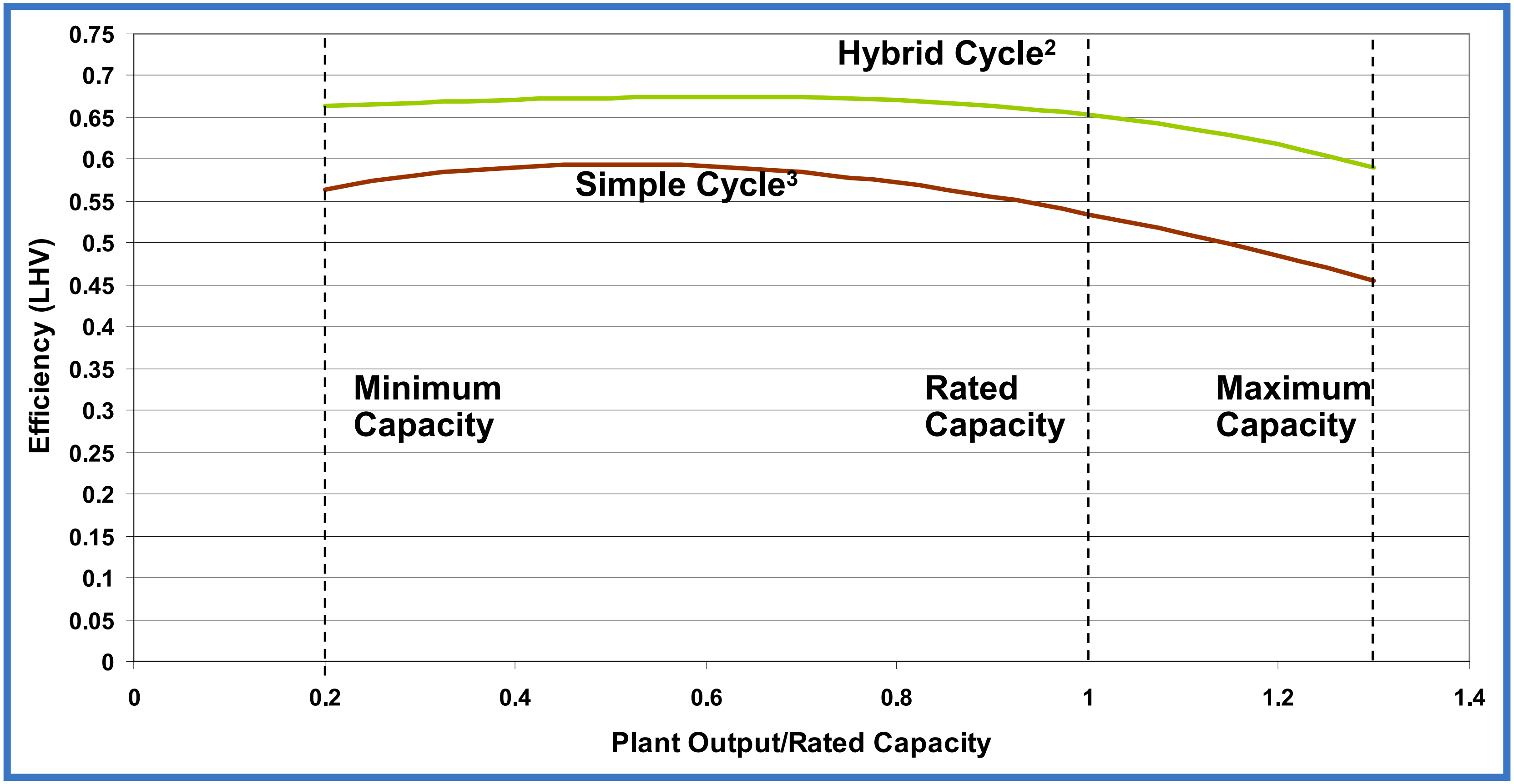
[1] See Appendix B for further details on system configuration. From:Scale-Up of Planar SOFC Stack Technology for MW-Level Combined Cycle System; TIAX LLC; Ref D0136; October 2003.

[2] Auxiliary fuel firing prior to the turbine inlet is needed to maintain turbine exhaust temperatures sufficient to heat the fuel cell inlet gases to 650°C.

We based simple-cycle performance on an atmospheric plant, and hybrid performance on a pressurized plant.

Parameter	Simple Cycle	Hybrid Cycle	Remarks
System Efficiency	54% LHV 49% HHV	66% LHV 60% HHV	◆At rated capacity ◆Includes inverter and power conditioning (95% efficient)
Cell Voltage	0.7 V		◆Cell voltage at rated capacity
Cell Power Density	360 mW/cm^2	430 mW/cm^2	◆Lower power density for the simple cycle system is because of the lower stack pressure (base load operation)
Operating Pressure	1 atm	3 atm	◆A 'direct system' i.e., combusted stack exhaust directly fed to turbine, is assumed for the combined cycle system
Fuel Processing	On-anode steam reforming		◆An external fuel processor is not required - lowers cost and improves efficiency
Fuel	Natural gas		◆Steam to carbon ratio of 2:1 is used
Fuel Utilization	90% utilization of hydrogen		◆Fuel utilization is specified in terms of utilization of the hydrogen that is produced from steam reforming of NG
Operating Temperature	650°C - 800°C		◆The temperature range corresponds to the inlet and exit temperatures of air from the stack.
System Exhaust Temperature	270°C	190	◆At rated capacity

We developed rough plant generation efficiency correlations as a function of load that allow for operation to 130% of rated capacity[1].



[1]Allowed operation up to 30% above rated capacity by allowing stack voltage (and efficiency) to drop. Allowed operation down to 20% of rated capacity.
[2]Rough estimate based on SECA study: Scale-Up of Planar SOFC Stack Technology for MW-Level Combined Cycle Systems; TIAX LLC; Ref. D0136; October 2003.
[3]Rough estimate based on SECA study: Scale-Up of 5-kW SECA Modules to a 250-kW System; TIAX LLC; Ref 74313; June 10, 2002.

We used capital-cost estimates that reflect the uncertainties in distribution-chain mark ups and installation costs.

- Capital Costs (Installed Costs)[1]:
  - Simple-Cycle Plant: $400/kW and $1000/kW
  - Hybrid Plant: $520/kW and $1400/kW
- Non-Fuel O&M:
  - Simple-Cycle Plant: $0.01/kWh
  - Hybrid Plant: $0.0125/kWh

Appendix C shows manufactured-cost estimates for each technology (not including distribution chain mark ups and installation).

[1] Low values are consistent with previous analyses and SECA targets. High values are consistent with mark ups experienced with HVAC equipment and appliances.

Agenda

- Purpose and Scope
- Description of Southpointe
- SOFC Technology Description
- **Analytical Approach**
- Waste-Heat-Utilization Possibilities
- Integration with Hydrogen Production
- Conclusions and Recommendations
- Appendices

Our performance model[1] uses an hour-by-hour analysis to estimate Overall Cost of Electricity (COE), energy savings, and emissions impacts.

Inputs

- Operating Strategy (Base-Load or Peak Shave)
- Plant Type
- Plant Rated Capacity
- Utility Rates
- Community Load Profiles
- Non-Fuel O&M Cost
- Plant Installed Cost
- Capital Recovery Factor
- Grid Efficiency[2]
- Grid Emissions Characteristics[3]

→

Hourly Model

- Plant Efficiency Correlations
- Plant Operating Algorithm
- Waste-Heat Production

→

Outputs

- Overall COE
- Capacity Factor
- Primary Energy Savings
- Emissions Impacts

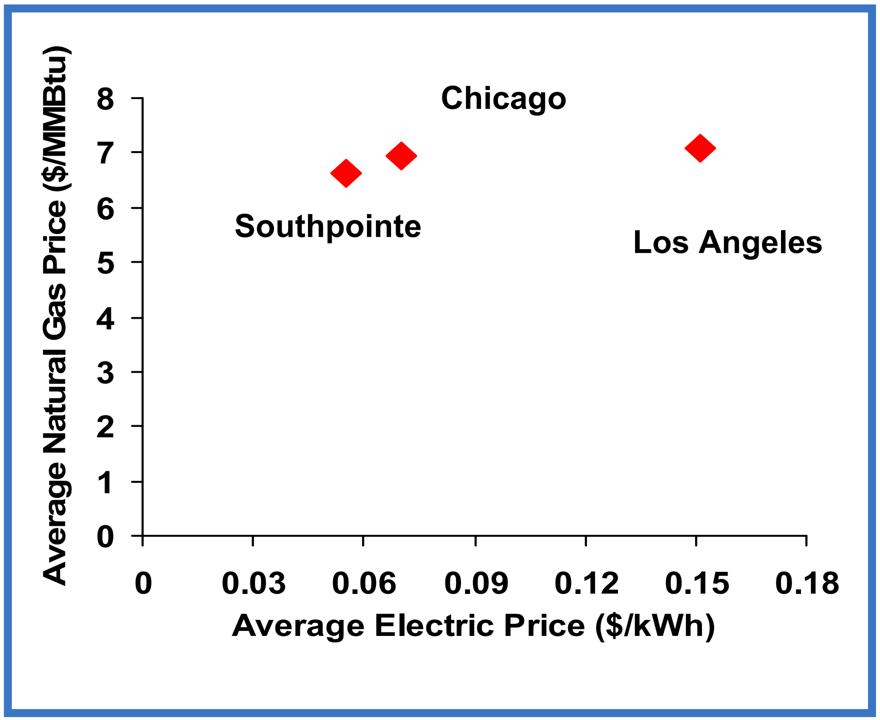
[1] Developed in MATLAB. Appendix D shows the decision tree for the hourly model
[2]Accounts for national average generation, transmission, and distribution losses.
[3] Based on national averages

Our Operational assumptions account for the impacts of actual utility rate structures.

- Value of generated electricity equals the retail price to the end user[1]
- Electric Rates:
  - Used electric rates for large office as a proxy for all end users
  - Accounted for demand charges, ratchet rates, and time-of-use pricing
  - Stand-by charges not included
  - Grid-parallel operation, but no power sold to grid
- Used natural gas rate appropriate for distributed generation

[1]See Appendix E for plausible business models

We evaluated operating costs for three utility rate structures to illustrate the impacts of rate structure on end-user economics. Southpointe is at the low end of the rate structures and Los Angeles is at the high end.



Rate Summary[1]				
City	Electric[2]			Gas[3] ($/MMBtu)
	Ratchet	Demand ($/kW)	Energy ($/kWh)	
Southpointe	√	$5.86	$0.041	$6.63
Chicago		$11.13-14.24	$0.023-0.056	$5.87-8.01
Los Angeles	√	$5.40-13.15	$0.054-0.30	$6.41-8.67

1) See Appendix F for detailed rates
2) For large office building, used as proxy for all end users. Excludes stand-by charges.
3) Rate suitable for large-scale DG/CHP, incorporating discounts where applicable

Estimates of primary energy savings and emissions reductions are based on the national average electric generation mix and projected performance characteristics for SOFC.

Generation Type	State	Primary Energy Efficiency	Emissions (lb/MWh)[1]		
			CO_2	SO_2	NO_x
Central Generation	Pennsylvania	–	1234	9.514	2.710
	Illinois	–	1109	4.932	2.707
	California	–	633	0.172	0.564
	National Average	**32.8% (HHV)[2] 36.3% (LHV)**	**1392**	**6.04**	**2.96**
SOFC DG	**Simple Cycle**	**–[3]**	**778**	**0.0068[4]**	**0.25[5]**
	Hybrid Cycle	**–[3]**	**659**	**0.00574[4]**	**0.225[5]**

More site-specific analysis of these benefits would be based on specific utility characteristics.

[1] For year 2000, from EPA Emissions & Generation Resources Integrated Database (eGRID) at www.epa.gov/cleanenergy/egrid/index.html

[2] Projected national average GT&D efficiency for 2005. From "Quality Guidelines for Energy System Studies"; Office of Systems and Policy Support; Table 5; September 30, 2003 Draft.

[3] See SOFC Technology Description section for SOFC efficiency correlations

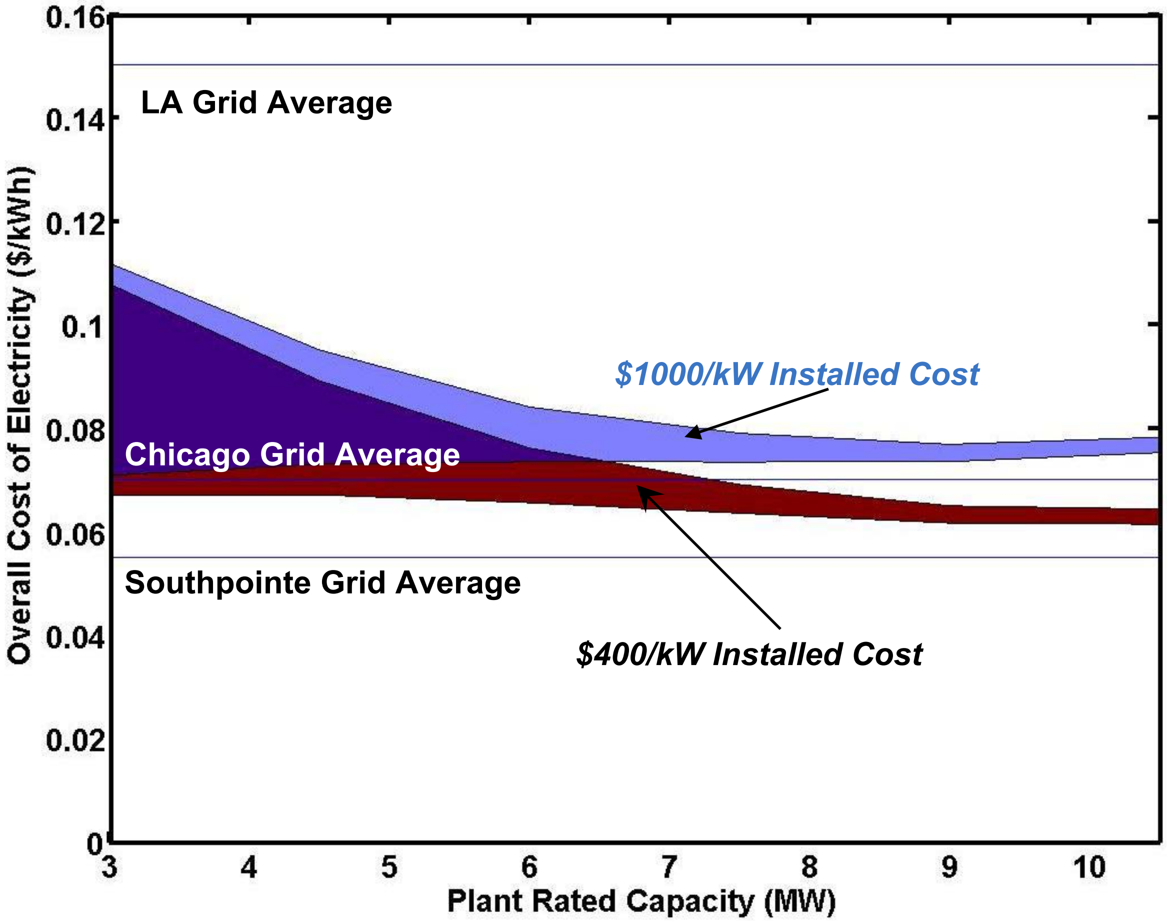
[4] Based on 1.0 lb. SO_2 per billion Btu of natural gas. From EIA; National Gas Issues and Trends; 1998.

[5] NO_x emissions are estimated at 10 PPM, representing a worse-case scenario (TIAX estimate).

The Overall Cost of Electricity (COE) includes both grid and generated electricity used by the community to facilitate comparisons among plants having different capacities.

- $COE = \dfrac{CR\ x\ Capital\ Cost + O\&M\ (non\text{-}fuel) + Fuel\ Cost + Grid\ Electric\ Cost}{Annual\ Community\ Electric\ Consumption}$
- CR = Capital Recovery Factor
  - Assumed to be 0.1 corresponding to favorable financing over an 8-10 year period
- O&M (non-fuel):
  - Routine maintenance (filters, lubrication, etc.)
  - Levelized cost of major subsystem/component replacements
    - Stack change outs
    - Replacement of catalysts in fuel processors

A detailed analysis shows that plant capacity has modest impacts on Overall COE for the simple-cycle plant[1].

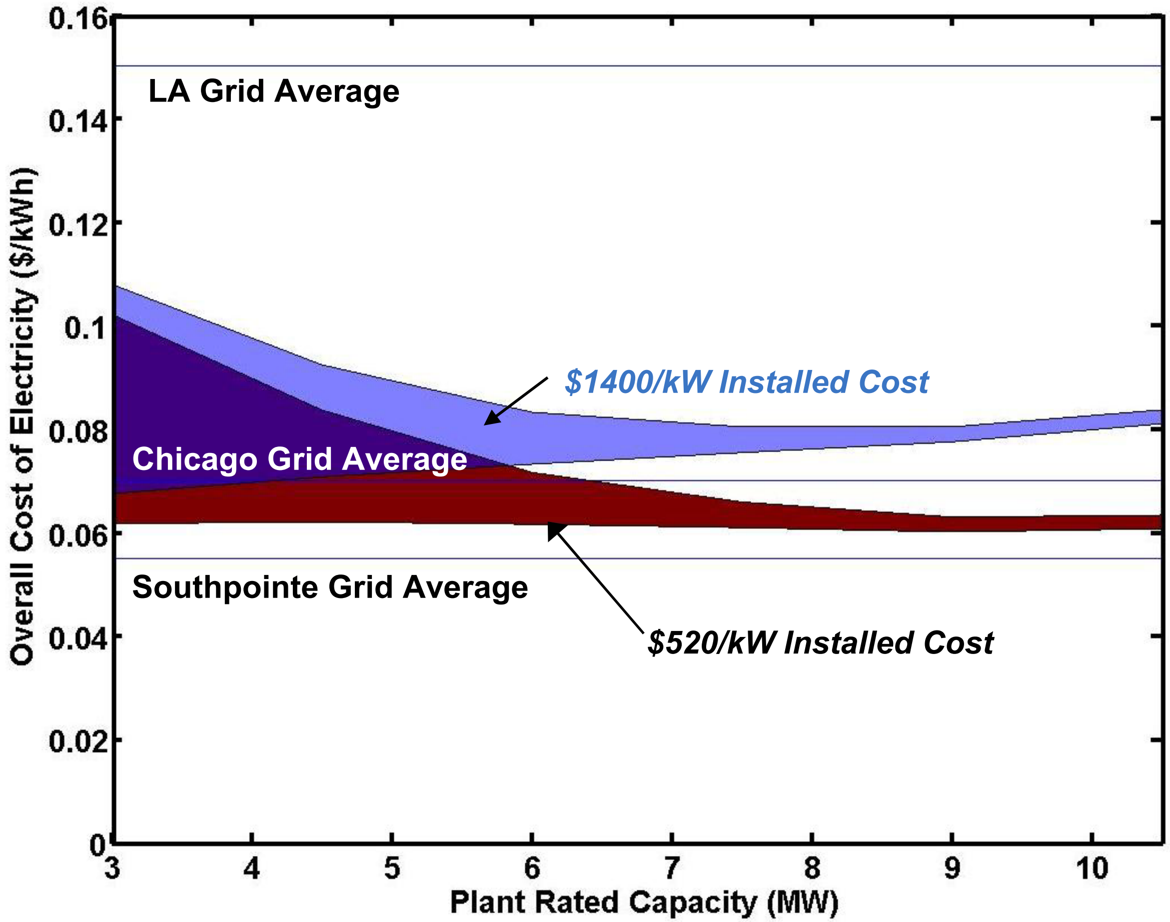


- Based on range of utility rates for each city
- Operation up to 30% over rated capacity
- Generation efficiency varies with load
- $0.01/kWh non-fuel O&M

Plant Rated Capacity (MW)	3	4.5	6	7.5	9	10.5
Capacity Factor[2]	1.2	1.0	0.82	0.69	0.58	0.50
Fraction of Load Generated[3]	0.69	0.86	0.95	0.99	1.0	1.0

[1]Simplified analysis shown in Appendix G
[2]Based on rated capacity
[3]Fraction of community electric load generated by DG plant.

A detailed analysis shows that plant capacity has modest impacts on Overall COE for the hybrid plant as well[1].



- Based on range of utility rates for each city
- Operation up to 30% over rated capacity
- Generation efficiency varies with load
- $0.0125/kWh non-fuel O&M

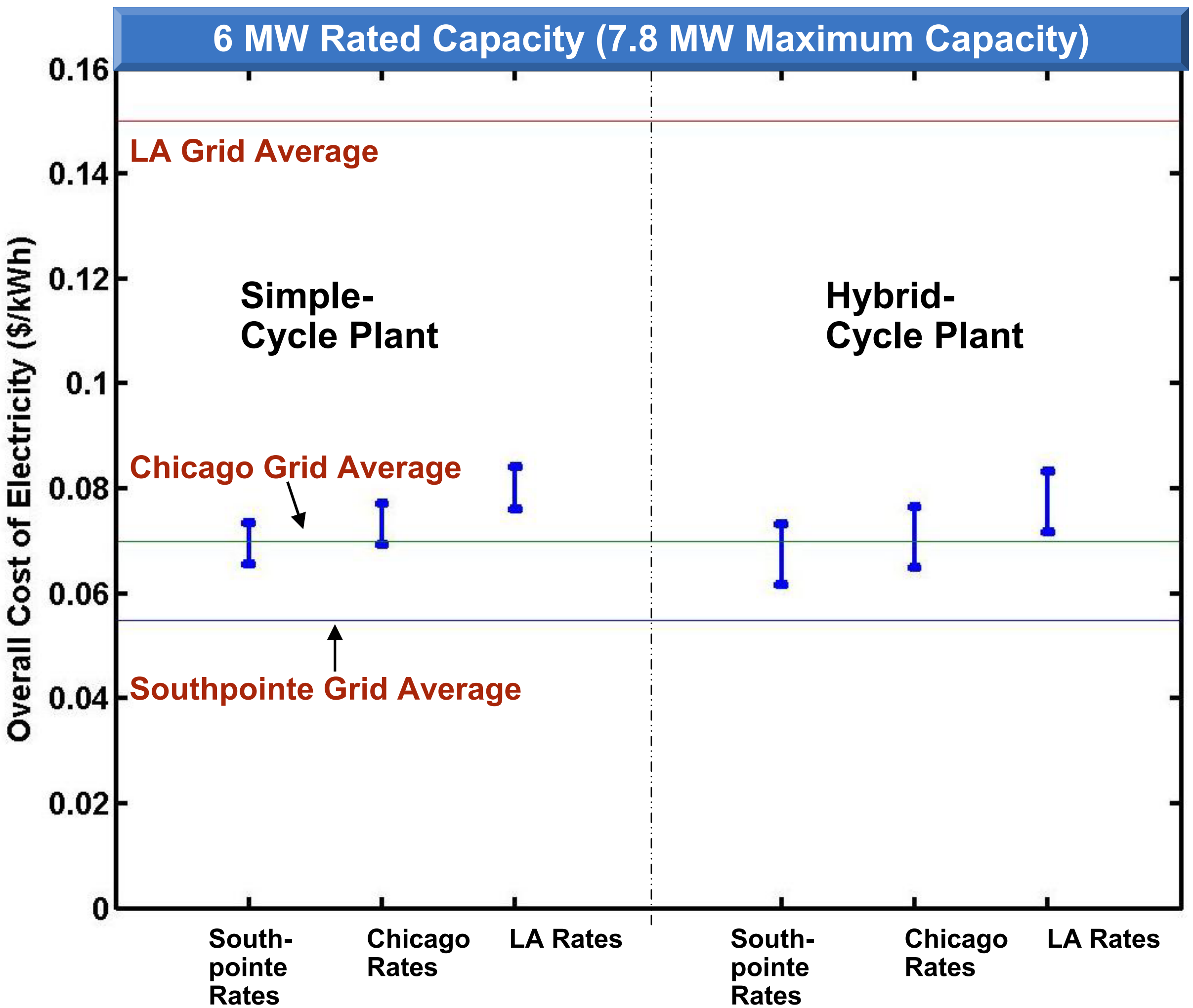
Plant Capacity (MW)	3	4.5	6	7.5	9	10.5
Capacity Factor[2]	1.2	1.0	0.82	0.68	0.58	0.50
Fraction of Load Generated[3]	0.69	0.86	0.95	0.99	1.00	1.00

[1]Simplified analysis shown in Appendix G
[2]Based on rated capacity
[3]Fraction of community electric load generated by DG plant.

These analyses and prior experience suggest that a 6 MW rated plant capacity (7.8 MW maximum capacity) will tend to maximize overall benefits.

- Results in a relatively high capacity factor of 0.82 (based on rated capacity), providing 95% of the community's electricity
- While lower-capacity plants have slightly better Overall COEs, they will provide reduced electric infrastructure, primary energy consumption, and emissions benefits
- Significantly higher-capacity plants will operate at lower Capacity Factors and, hence, have less attractive energy delivery economics

End-user economics alone can justify SOFC plant installation for medium-to-high utility rate structures[1].

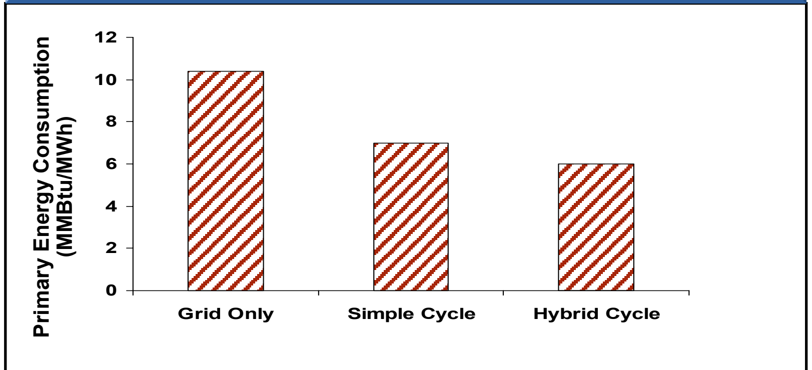


Utility Rate	Simple Cycle Range ($/kWh)[2]	Hybrid Cycle Range ($/kWh)[3]
Southpointe	$0.061-0.069	$0.055-0.066
Chicago	$0.065-0.072	$0.058-0.069
LA	$0.071-0.079	$0.065-0.076

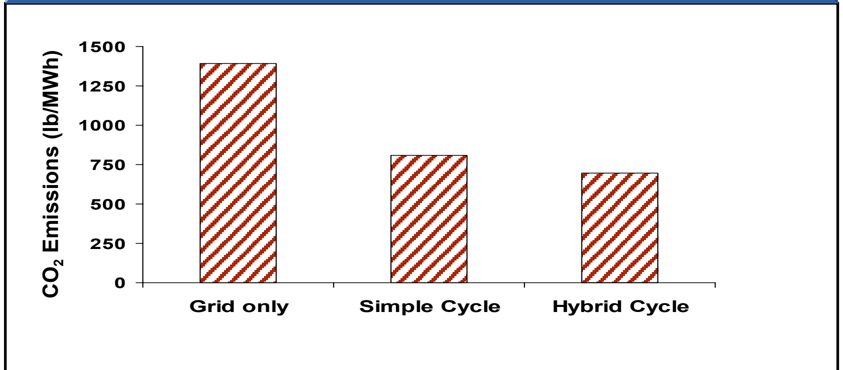
[1]See Appendix H for further breakdown in overall COEs.
[2]Simple-cycle capital costs were modeled between $400/kW and $1000/kW (rated capacity)
[3]Hybrid-cycle capital costs were modeled between $520/kW and $1400/kW (rated capacity)

The SOFC plants can reduce community primary energy consumption by 35 to 45% for a 6 MW rated capacity, with significant emissions benefits as well.

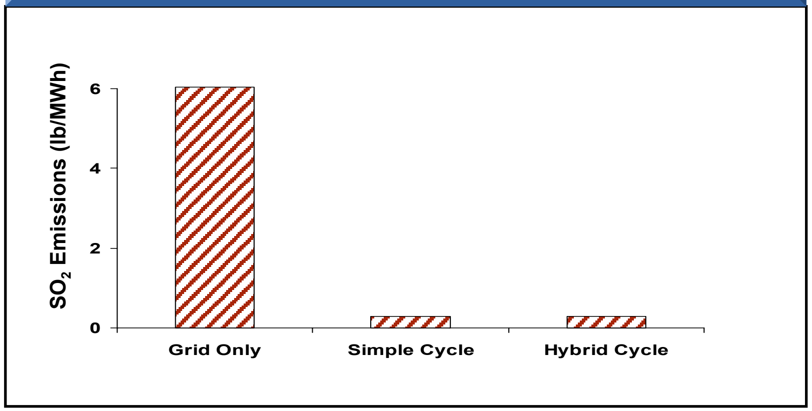
Primary Energy[1]



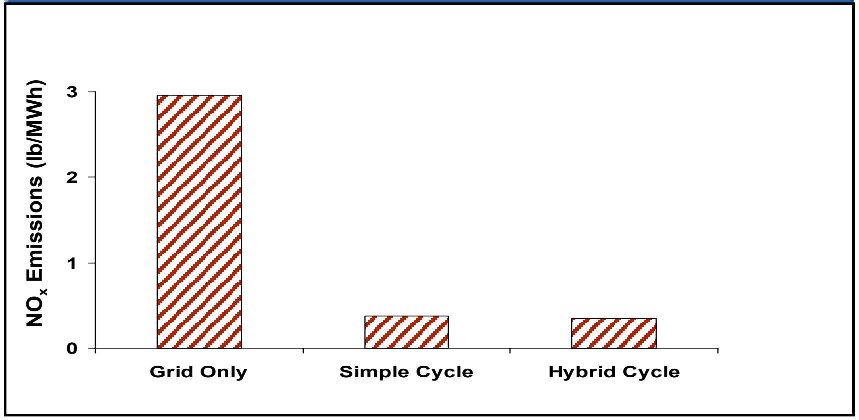
CO_2 Emissions[2]



SO_2 Emissions[2]



NO_x Emissions[2]



[1]Grid consumption is based on projected National Average GT&D efficiency of 32.8% (HHV) [36.3% (LHV)] for 2005. From Quality Guidelines for Energy System Studies, Office of Systems and Policy Support; Table 5; September 30, 2003 Draft.
[2]Grid emissions are based on national averages for 2000. From EPA eGRID.

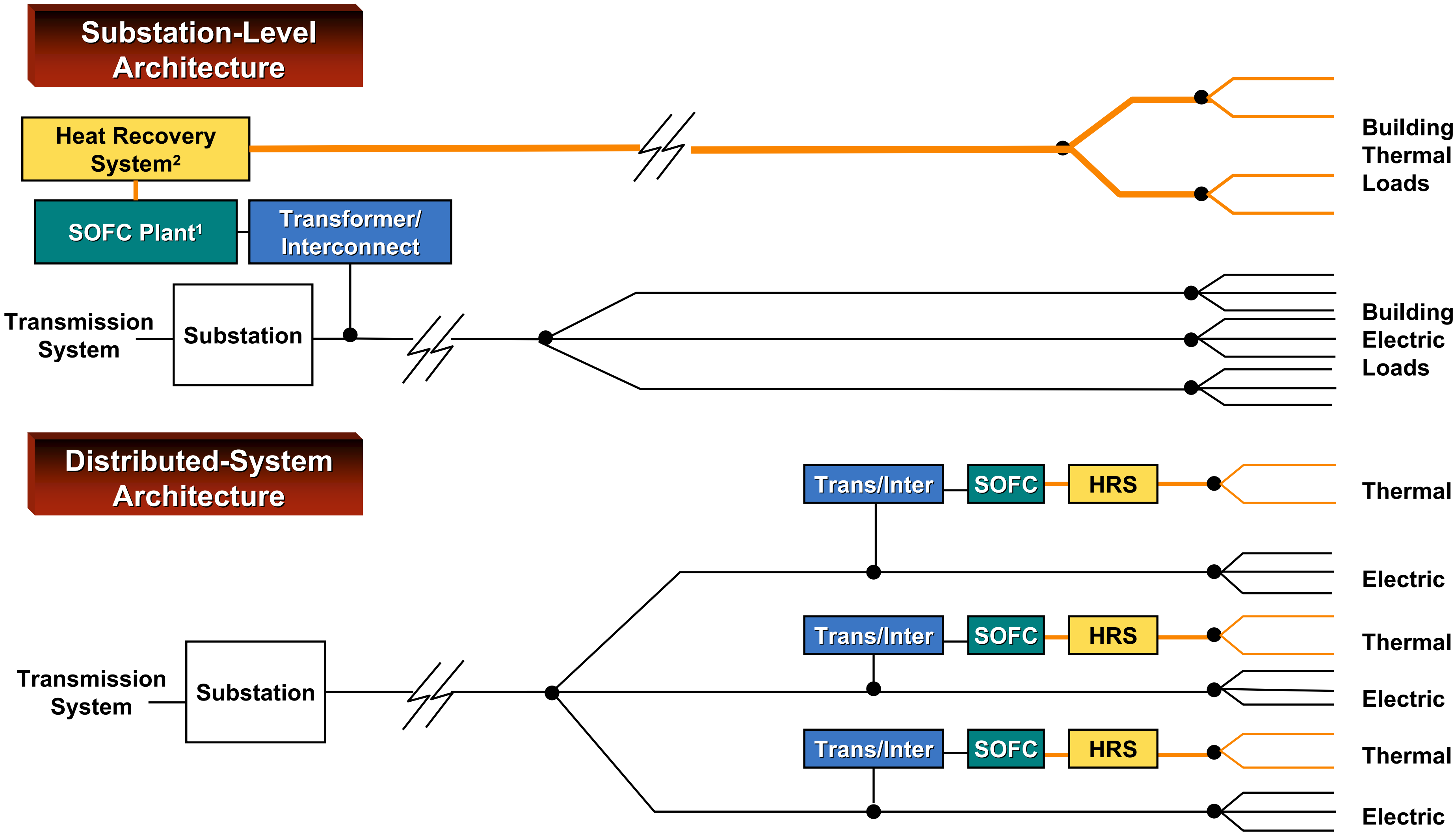
Agenda

- Purpose and Scope
- Description of Southpointe
- SOFC Technology Description
- Analytical Approach
- **Waste-Heat-Utilization Possibilities**
- Integration with Hydrogen Production
- Conclusions and Recommendations
- Appendices

We identified waste-heat-utilization possibilities within the community for each technology and roughly estimated energy cost impacts.

- Building space and water heating
- Building space cooling

We considered two system architectures.

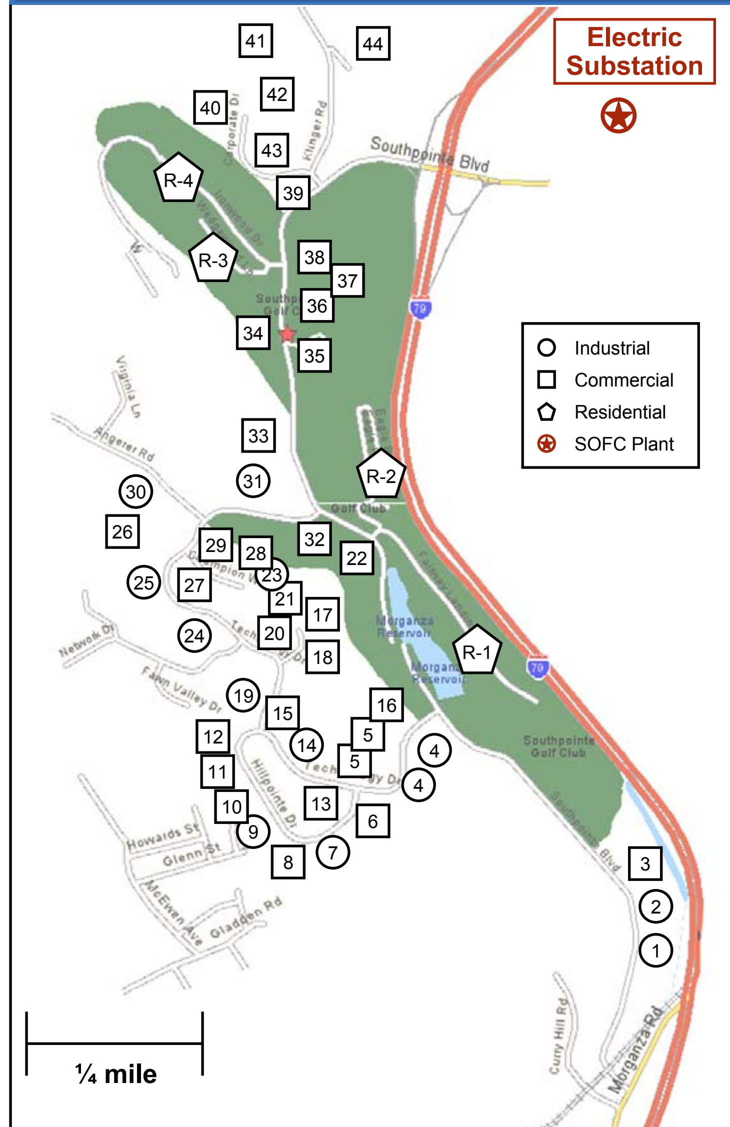


[1] Simple-cycle or hybrid plant
[2] Heat Recovery may or may not be used

The SOFC plant is sited adjacent to the substation for the substation-level architecture.

- 7 miles of piping will reach 56% of community thermal load
- $1.5MM for piping, valves, controls (rough estimate based on $20/ft for piping, $20/ft of piping for valves, controls)

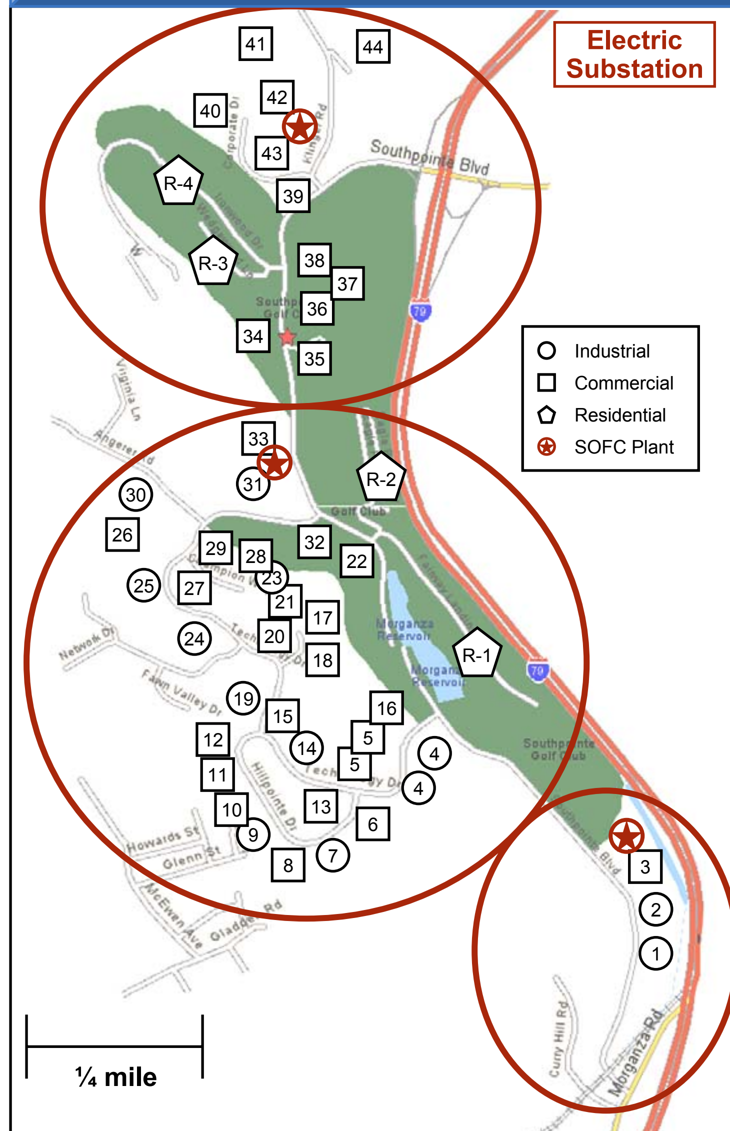
Community Layout[1]



The Southpointe community has three primary building clusters that dictate logical plant siting for the distributed architecture.

- 4.3 miles of piping will reach 61% of community thermal load
- $1 MM for piping, valves, controls (rough estimate based on $20/ft for piping, $20/ft of piping for valves, controls)

Community Layout[1]



The Distributed Architecture may have advantages for utilization of waste heat and load management during grid outages[1].

Waste-Heat Utilization

- Reduces cost of piping runs by $0.5 million (rough order of magnitude)
- Reduces thermal losses and pumping parasitics
- Do not need to pipe under interstate highway

Load Management

- Requires less sophisticated control system to direct generated electricity to premium-power customers during a grid outage (assuming critical loads are primarily associated with larger energy consumers)

[1]See Appendix I for further discussion of siting issues.

The relatively high reject-heat temperatures of SOFC provide a high level of utilization flexibility.

- Both simple and hybrid cycles can interface with conventional space- and water-heating functions
- The reduced exhaust temperatures of hybrid cycles are consistent with operation of single-effect absorption equipment[1]
- The high-temperature reject heat from simple-cycle architecture can drive highly efficient double-effect absorption equipment, but double effect offers little cooling capacity advantage[1]

[1] See Appendix J for exhaust-stream characteristics

We roughly estimated the energy-consumption and energy-cost impacts of waste-heat utilization.

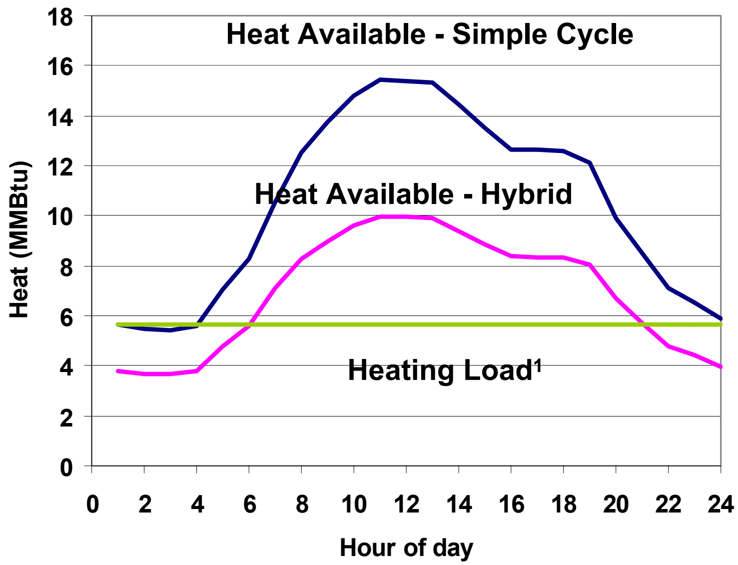
- Heat Recovery for Heating (Commercial and Residential)
  - Assumed all natural-gas consumption is for heating
  - Assumed 80% (HHV) efficiency for all heating equipment
- Heat Recovery for Cooling (Commercial only)
  - Roughly estimated commercial cooling loads (see Appendix K)
  - Single-effect absorption chillers (0.6 COP)[1]
- Neglected other cooling and heating loads
  - No industrial gas usage was reported in NETL load profiles
  - Industrial electric consumption profiles suggest little electricity used for cooling

[1] While single-effect absorption chillers have COPs higher than this value (typically 0.7), COP was adjusted to roughly compensate for the increase in electric parasitic loads (for condenser pumps and cooling tower fans) associated with absorption chillers. Assumes that absorption cooling will be practical in all commercial buildings, even those currently using air-cooled electric chillers or unitary air conditioners.

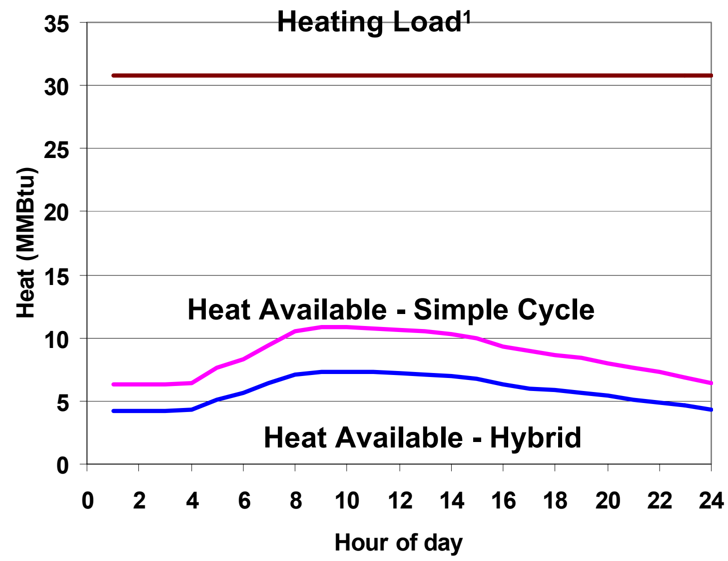
Waste-heat recovery can serve a portion of community heating loads.

6 MW Rated Capacity (7.8 MW Maximum Capacity)

Average Summer Day



Average Winter Day



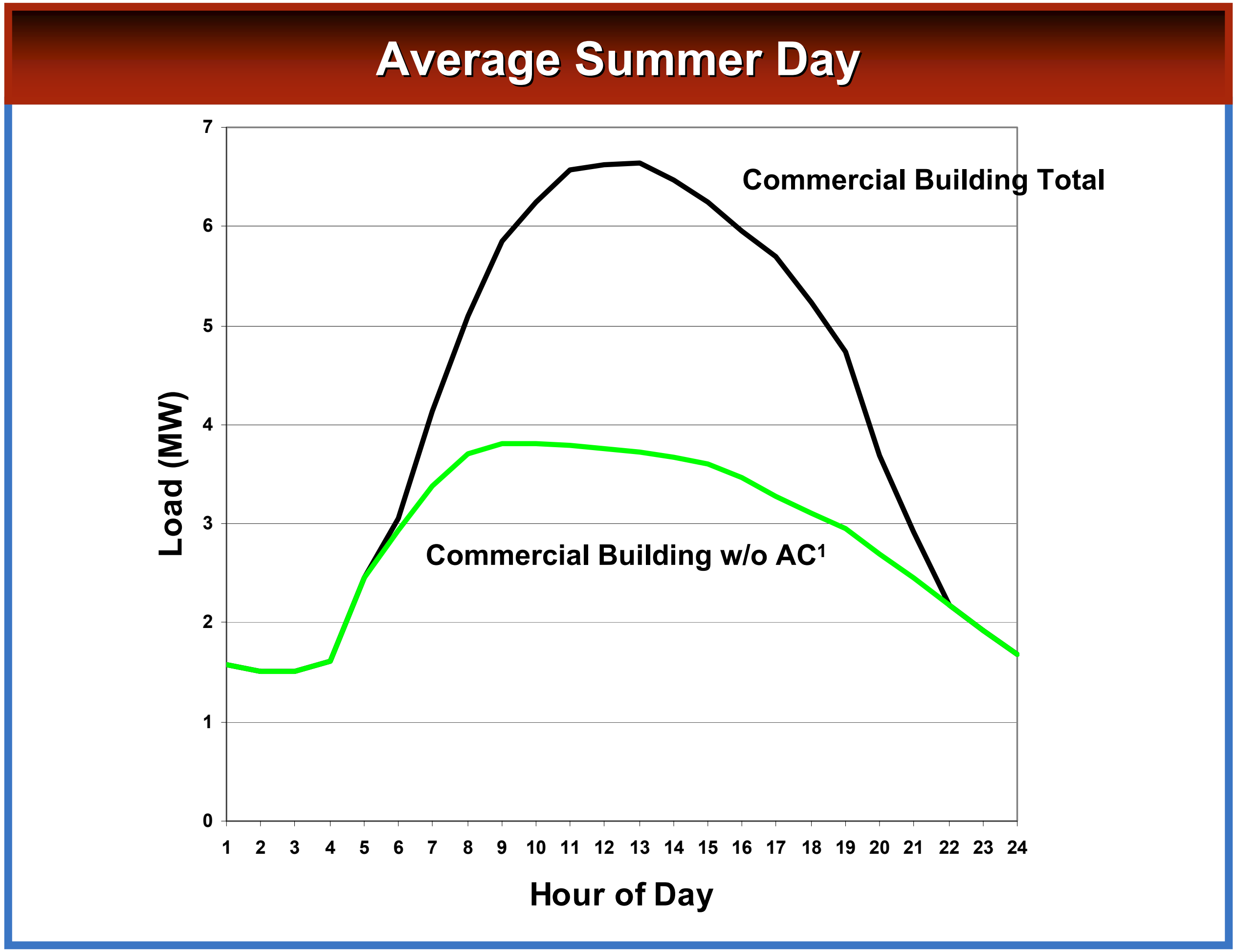
[1]Assumes 0.80 (HHV) average heating efficiency. Hourly values were not provided – only daily averages.

Heat recovery can reduce heating gas consumption by roughly 40 to 45%.

Rough Heating Load Savings[1]		
	Simple Cycle	**Hybrid Cycle**
Useful Heat from Plant, Summer	1.6 MW_{th} (5.5 MMBtuh)	1.6 MW_{th} (5.5 MMBtuh)
Useful Heat from Plant, Winter	2.2 MW_{th} (8.3 MMBtuh)	1.7 MW_{th} (5.8 MMBtuh)
Annual Mean[2]	1.9 MW_{th} (6.5 MMBtuh)	1.7 MW_{th} (5.8 MMBtuh)
Annual Gas Cost Savings[3]	$489,000 (43%)	$436,000 (38%)

[1]Accounts for natural gas savings, based on 0.80 (HHV) [0.89 (LHV)] typical heating-equipment efficiency and gas rates from Appendix F.
[2]Rough estimate based on simple averages of summer and winter usable heat available for community heat loads.
[3]Community average rate of gas consumption is 5.57 MW_{th} (19 MMBtuh). Neglects thermal losses in piping. Based on $6.87/MMBtu (average rate of Southpointe, Chicago, and Los Angeles).

In the summer, commercial building cooling adds 2.9 MW to peak electric loads, on average.



[1] See Appendix K for methodology for estimating cooling electric loads.

Heat Recovery for Cooling can reduce electric demand by an additional 0.9 MW for a 6 MW simple-cycle plant.

Plant Type	Operating Capacity (MW)	Total Reject Heat	Available Heat for Cooling[1]	Reduction in Electric Demand for Cooling[2]
Simple Cycle	6	6.25 MW_{th} (21.3 MMBtuh)	3.07 MW_{th} (11.6 MMBtuh)	0.46 MW_e
	7.8 (130% of Rated Capacity)	10.77 MW_{th} (36.7 MMBtuh)	5.95 MW_{th} (20.3 MMBtuh)	0.90 MW_e
Hybrid Cycle	6	4.05 MW_{th} (13.8 MMBtuh)	1.44 MW_{th} (4.91 MMBtuh)	0.22 MW_e
	7.8 (130% of Rated Capacity)	6.64 MW_{th} (22.7 MMBtuh)	2.90 MW_{th} (9.89 MMBtuh)	0.44 MW_e

[1]Based on minimum exhaust temperature of 82ºC for single-effect absorption. Neglects thermal losses in piping.
[2]Based on single-effect absorption chiller COP of 0.6 and displaced electric cooling equipment averaging 0.8kW/ton (4.4 COP). See Appendix K for further details.

Cooling with waste heat can reduce energy costs by $50,000 to $500,000, depending on rate structures and SOFC technology.

Rough Cooling Cost Savings for 6 MW Rated Capacity (7.8 MW Maximum)[1]

Rate Structure	Plant Type	Demand Savings	Energy Savings	Total[2]
Southpointe	Simple	$44,000	$71,000	$110,000
	Hybrid	$21,500	$35,500	$57,000
Chicago	Simple	$38,500	$70,000	$108,500
	Hybrid	$19,000	$35,000	$53,000
Los Angeles	Simple	$57,500	$441,000	$498,500
	Hybrid	$28,000	$220,500	$248,500

[1]Based on 0.90 MW (simple) or 0.44 MW (hybrid) reduction in peak over three summer months, and includes ratchet effect for Los Angeles and Southpointe.

[2] Rough estimate: based on average summer day savings of 0.7 MW (simple) or 0.35 MW (hybrid) for fourteen hours per day. Average summer day savings are based on average waste heat available for cooling during the summer months, which are lower than the peak values of 0.9 MW and 0.44 MW due to decreased electrical loads on weekends. Annual energy savings for cooling (in kWh) were estimated to be twice summer energy savings.

Agenda

SOFC installations can support the production and delivery of hydrogen for transportation applications via multiple technology strategies[1].

H_2 Production Strategy	Pros
1. Utilize off-peak electricity from SOFC for high- efficiency electrolysis	◆ Improves SOFC capacity factor ◆ Electrolysis units are commercially available ◆ DOE programs are focussing on efficiency and cost improvements ◆ Potential for high-pressure and high-purity hydrogen
2. On-anode reforming (during off peak)	◆ Improves SOFC capacity factor ◆ High gas-to-hydrogen efficiency (60-70% LHV including power for reformate compressor[1]) ◆ Potential for relatively low-cost hydrogen
3. Use waste heat to support separate steam reforming process	◆ Could reduce natural gas use in hydrogen generation by 20%[1]
4. Use waste heat to operate H_2 absorption storage technologies	◆ Absorption storage is safer than compressed gas and can operate at lower pressure ◆ Eliminates compression power if low-pressure hydrogen is required (e.g., fuel-cell power systems) ◆ High-temperature waste heat can be used to thermally compress hydrogen if high pressure is required[1] ◆ Can be used with a stand-alone reformer or in conjunction with the above strategies

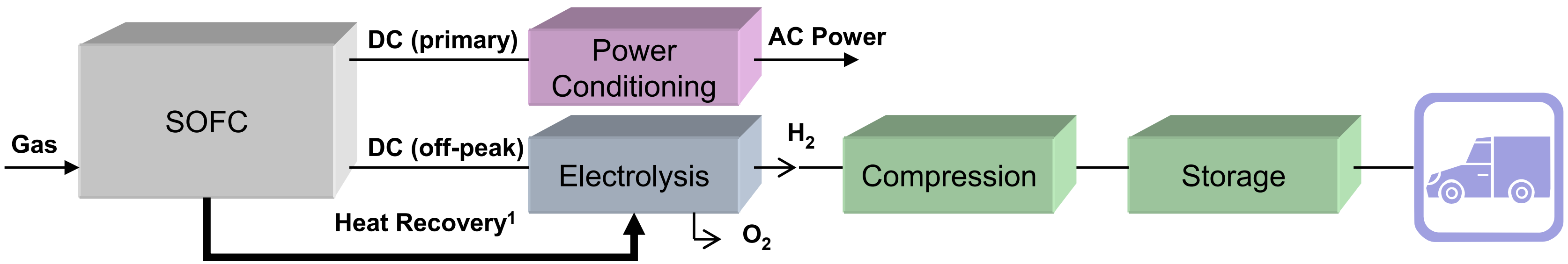
[1] Requires validation using detailed system designs.

However, more detailed analysis will be required to prove out these concepts and investigate potential barriers to their implementation.

H_2 Production Strategy	Cons
1. Utilize off-peak electricity from SOFC for high-efficiency electrolysis	◆ Relatively low gas to hydrogen efficiency (30-45% LHV[1]) ◆ Electrolysis economics not attractive unless power is cheap ◆ Low electrolyser capacity factor ◆ Must be competitive with low-cost off-peak electricity from the grid
2. On-anode reforming (during off peak)	◆ Shift reactors, purification system, and reformate compressors are required to produce pure hydrogen, adding cost and power requirements ◆ Hydrogen outlet pressure is relatively low (~130 psia for PSA)
3. Use waste heat to support separate steam reforming process	◆ Requires separate reformer and purification system ◆ Benefit may not be significant if purification system off-gasses are already effectively utilized
4. Use waste heat to operate H_2 absorption storage technologies	◆ Typical absorption materials (e.g., metal hydrides) are relatively expensive compared to compressed gas storage ◆ A significant amount of high-temperature waste heat is required

[1] Requires validation using detailed system designs.

The use of SOFC electricity to operate electrolysis units would be particularly attractive in the near-term to fuel demonstration hydrogen vehicles. Longer term, heat recovery could be used for high-temperature electrolysis.



- DC power from SOFC is used directly in commercially available electrolysis units
- For a high-efficiency SOFC hybrid, gas-to-hydrogen efficiency might approach 30-45% (LHV)[2]
- Could refill 100+ hydrogen vehicles per day assuming 5-6 kg/fill (~200-350 mile range)
  - 3 MW of excess capacity for an average of 11 hours per day produces 600-700 kg/day of hydrogen, with oxygen as a biproduct
  - Hydrogen could be produced at low (conventional) or high pressure (advanced technologies are approaching 3,600 psia), depending on the electrolyser design
- SOFC capacity factor is improved, but the electrolyser capacity factor will be relatively low (<50%)
  - Could result in a relatively high cost for hydrogen unless the cost of electricity is very low
- Note that all these strategies require hydrogen storage and/or delivery

[1]Heat recovery can be used for future, high-temperature electrolysis

[2]Assuming 54-66% (LHV) SOFC efficiency on natural gas and 60-70% (LHV) electrolyser efficiency. Requires validation using detailed system designs.

Agenda

- Purpose and Scope
- Description of Southpointe
- SOFC Technology Description
- Analytical Approach
- Waste-Heat-Utilization Possibilities
- Integration with Hydrogen Production
- **Conclusions and Recommendations**
- Appendices

A community-based SOFC DG or CHP system can provide multiple benefits.

- A SOFC plant capacity of 6 MW rated (7.8 MW maximum) is well suited for the load profile of the Southpointe community, and provides approximately 95% of the community's electric load.
- A simple-cycle SOFC plant can reduce primary energy consumption by approximately 35% for a community such as Southpointe.
- A hybrid SOFC plant can reduce primary energy consumption by approximately 45%.
- Either SOFC plant can reduce NO_x and SO_2 emissions by an order of magnitude for the Southpointe community[1].
- Because Southpointe electric rates are very low, benefits other than end-user economics (such as T&D support and power quality/reliability) must be considered to justify SOFC plant installation.

[1]Based on national average grid emissions. Emissions benefits vary significantly depending on the sources for grid electricity. For example, in California the emissions impacts would be modest.

- With Chicago rates, end-user economics alone can justify SOFC plant installation at the low end of the installed-cost ranges considered.
- With Los Angeles rates, end-user economics alone can justify SOFC plant installation across the range of installed costs considered.
- Recovering waste heat for heating can lower community natural-gas consumption by about 40 to 45%, saving $440,000 to $490,000 annually.
- Recovering waste heat from the simple-cycle plant to drive absorption cooling can reduce peak demand by an additional 0.9 MW for the average summer day. For the hybrid plant, summer peak-load reductions are about 0.4 MW. The associated electricity-cost savings range from $50,000 to $500,000 depending on technology and utility rate structure.
- Installing multiple SOFC plants within the community can reduce the costs associated with waste-heat utilization. Capital-cost savings for piping alone would be roughly $0.5 million.
- There are several ways that a community-based SOFC plant can potentially support hydrogen production and delivery.

This initial analysis of a community-based SOFC system suggests several important areas for further study.

Hydrogen Possibilities

- More detailed analysis of four options to support hydrogen production and delivery

Other Benefits

- Monetize the T&D-support, premium-power, and emissions-reduction benefits

Waste-Heat Utilization

- More detailed analysis of waste-heat utilization, including economic analysis
  - Locating plants next to thermal loads
  - Single- vs. double-effect absorption cooling
  - Locating absorption chillers at SOFC plants or at building

Appendices

- Appendix A: Details of NETL-Supplied Load Profiles
- Appendix B: System Configuration Electrical Connections
- Appendix C: Conceptual Cost Estimates
- Appendix D: Model Decision Trees
- Appendix E: Plausible Business Models
- Appendix F: Utility Rate Details
- Appendix G: Simplified Analysis
- Appendix H: Detailed Analysis
- Appendix I: Siting Issues
- Appendix J: SOFC System Exhaust Characteristics
- Appendix K: Approximation of Commercial Building Cooling Loads

Southpointe consists of a mix of commercial, light industrial, and residential buildings.

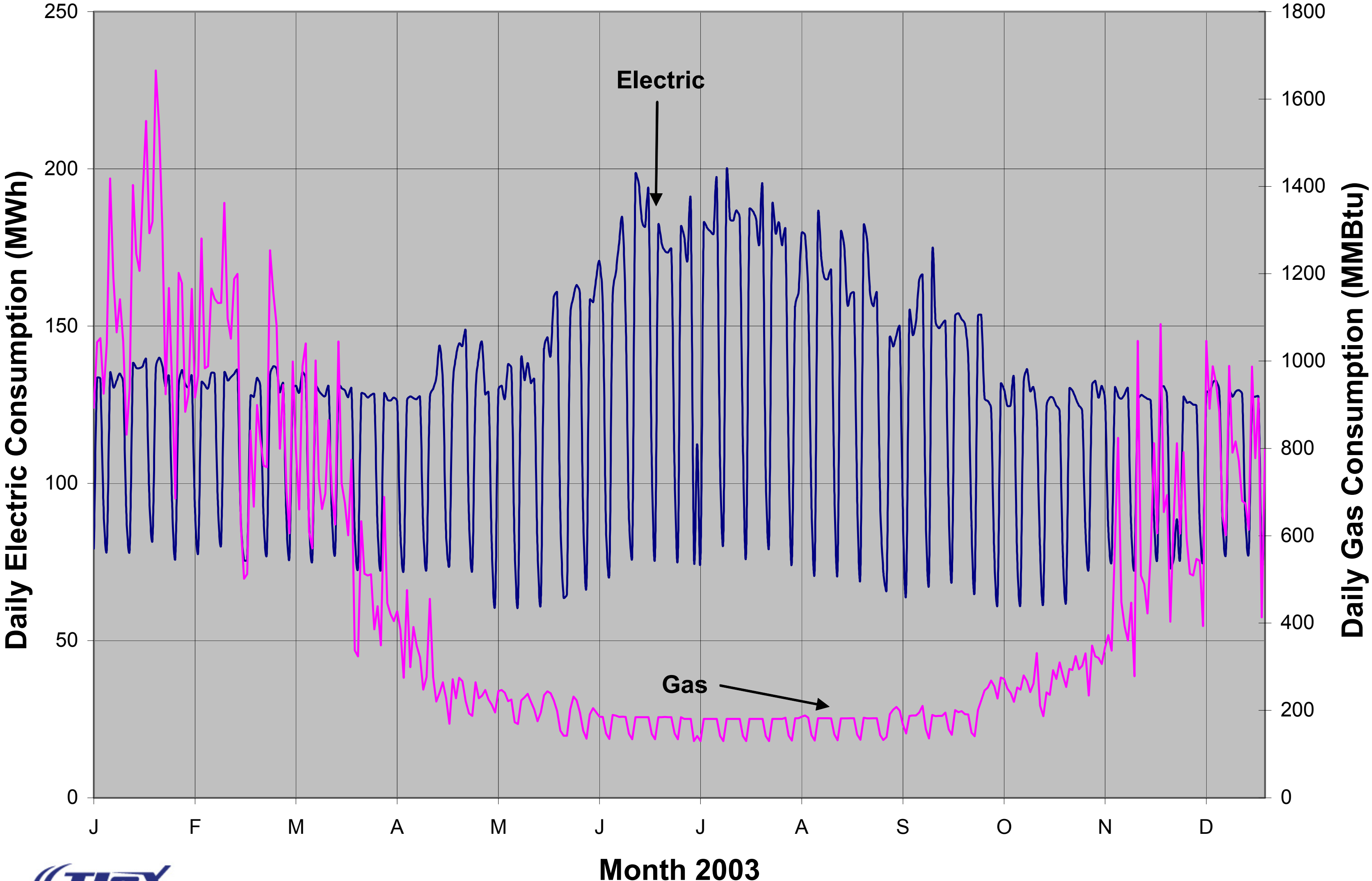
- Commercial Buildings
  - 9 large offices ~1MM square feet total, 1200 employed
  - 13 medium offices, ~550K square feet, 1300 employed
  - 11 small offices, ~200K square feet, 300 employed
  - 1 Hotel, 135K square feet, 100 employed
  - 3 Public Assembly Buildings, 128K square feet, 200 employed
- Industries, 9 Companies
  - Printing, Fabricated Metal Products, Surgical Equipment Manufacturers, Office Equipment Manufacturers
  - ~ 450K square feet total, 800 people employed
- Residences
  - 40 Single-Family Homes, 1700 square feet per home
  - 79 Townhouses, 1000 square feet per home
  - Luxury apartments, 120K square feet total

NETL generated load profiles for Southpointe (for 2003) using eShapes[1] for use in this assignment.

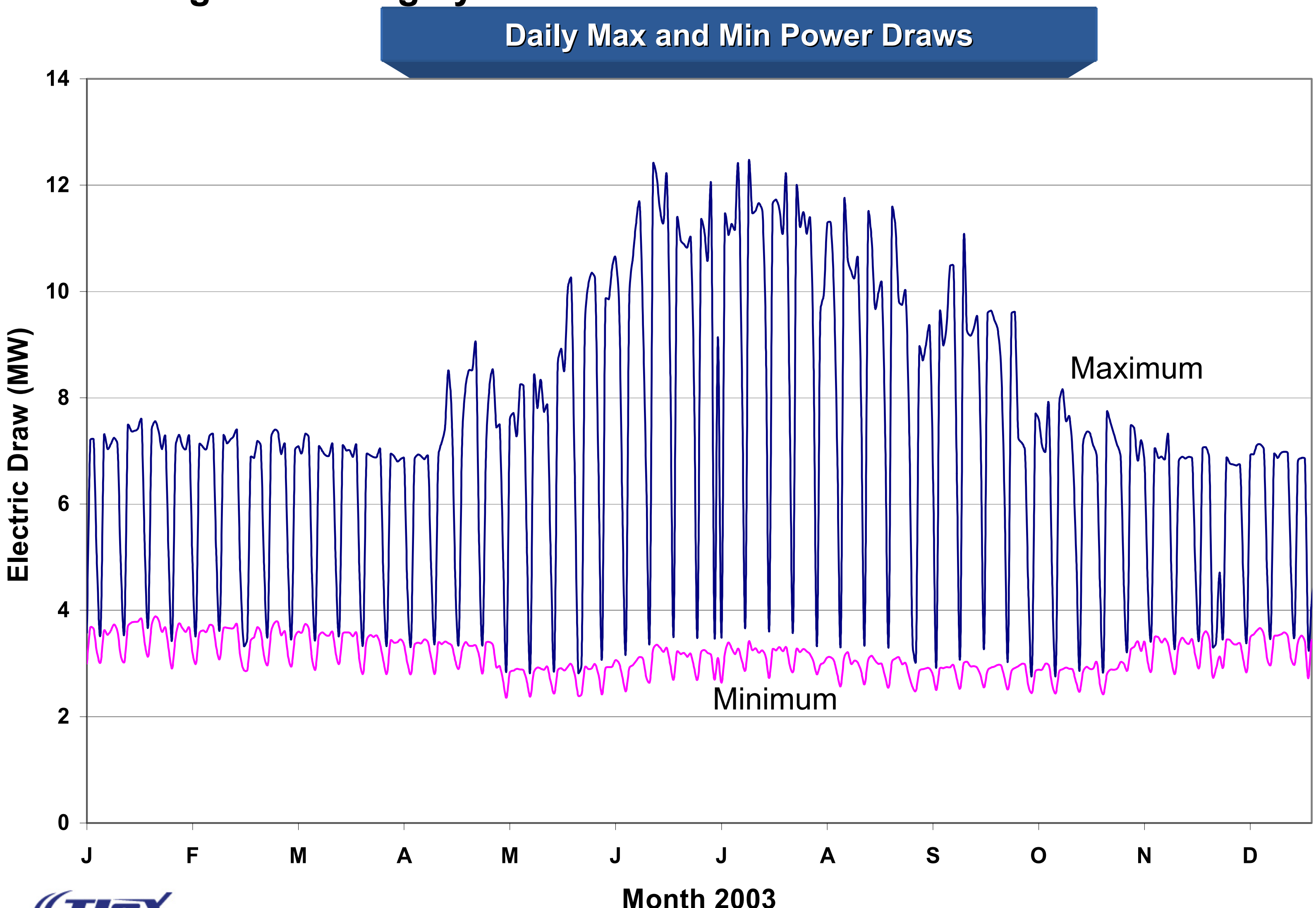
- Electric and natural gas profiles generally appear consistent with TIAX experience for similar building types and climates
- Load profiles are more smoothed than typical for individual end users. This could result in slight underestimate of demand-charge savings
- Profiles show no natural gas use for industrial buildings, which seems unusual
- Hourly electric consumption and daily gas consumption provided on per-building basis

[1]eShapes, available from Itron, Inc., provides typical electric and gas load profiles for many industrial, commercial, and residential building types.

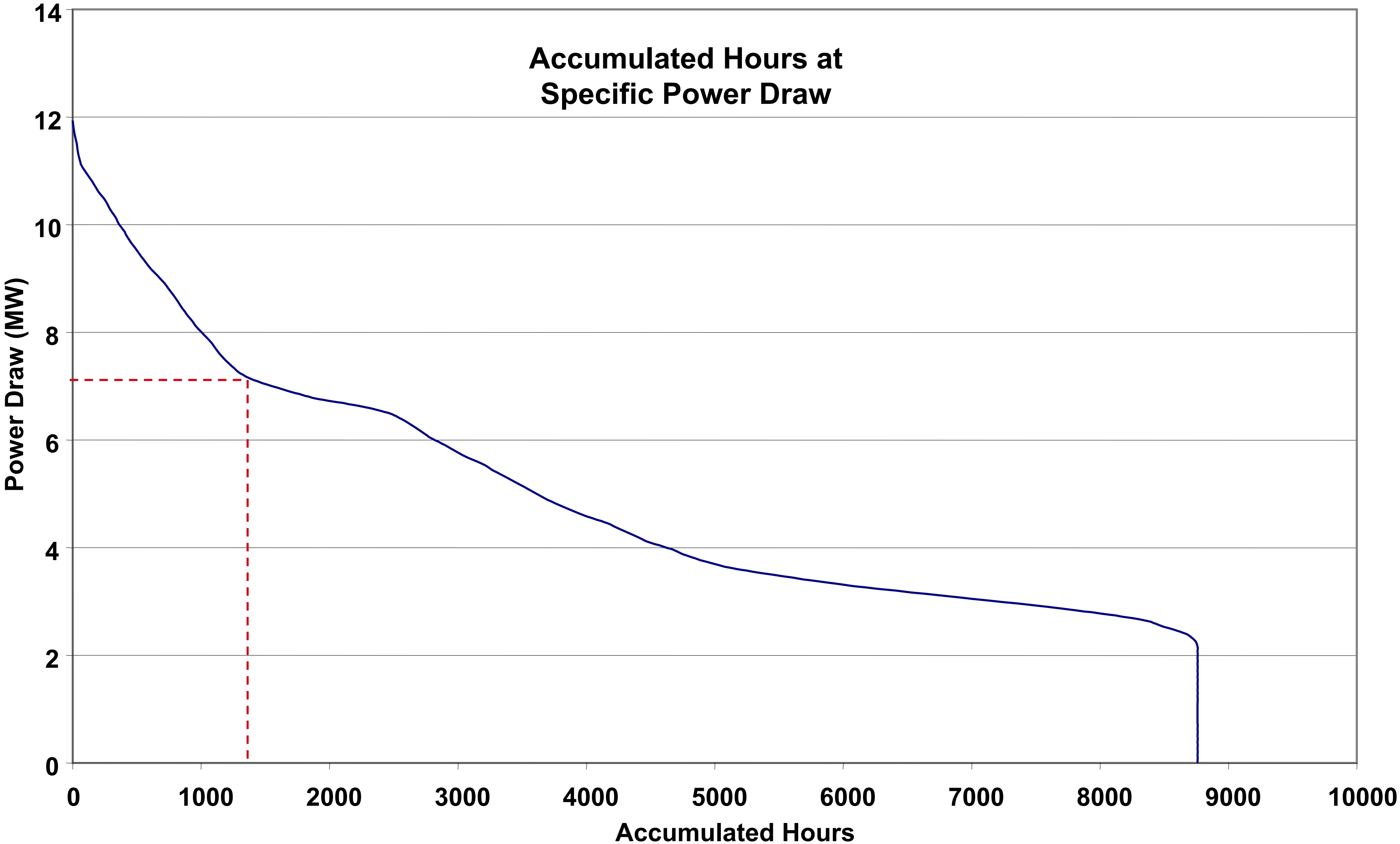
Daily Electric and Gas Consumptions range from 60-200 MWh and 40-480 MWh (140-1600 MMBtu), respectively.



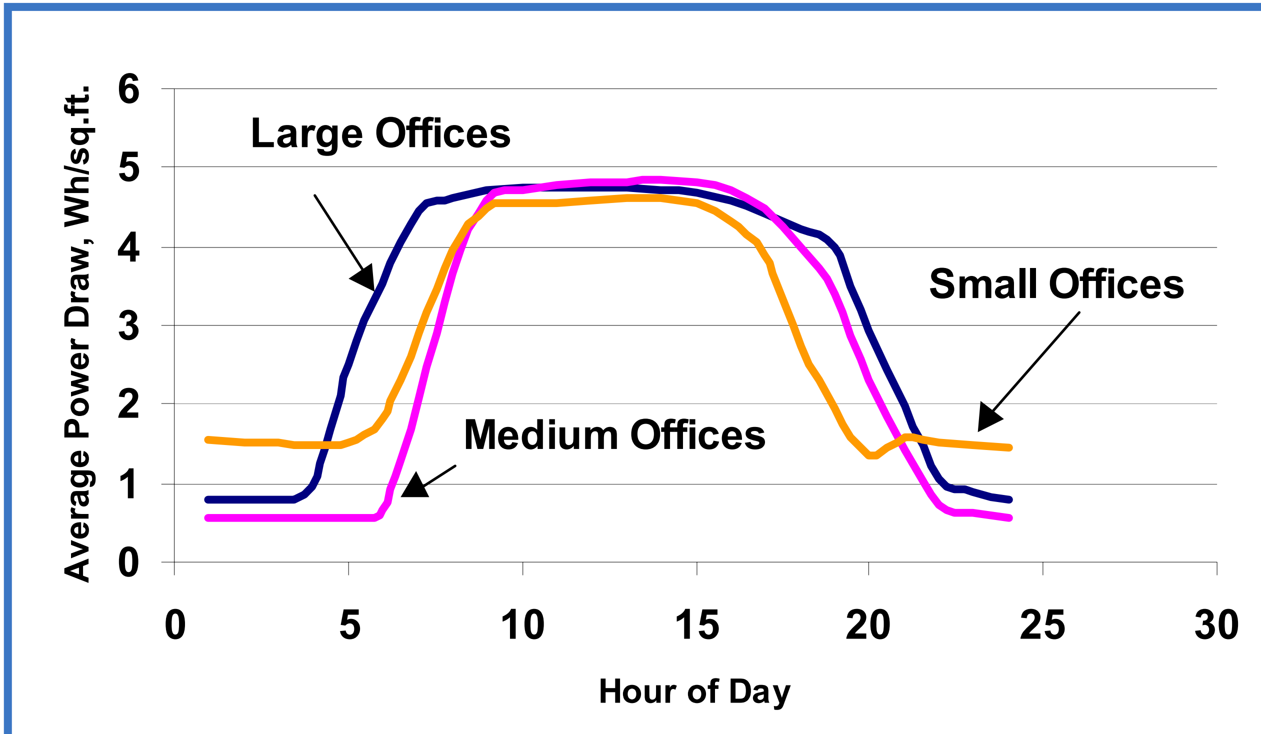
Peak daily draws range from roughly 2.6 MW to 12.4 MW, while minimum daily draws range from roughly 2.3 MW to 3.9 MW.



Electric loads are below 7 MW for 83 percent of the year.

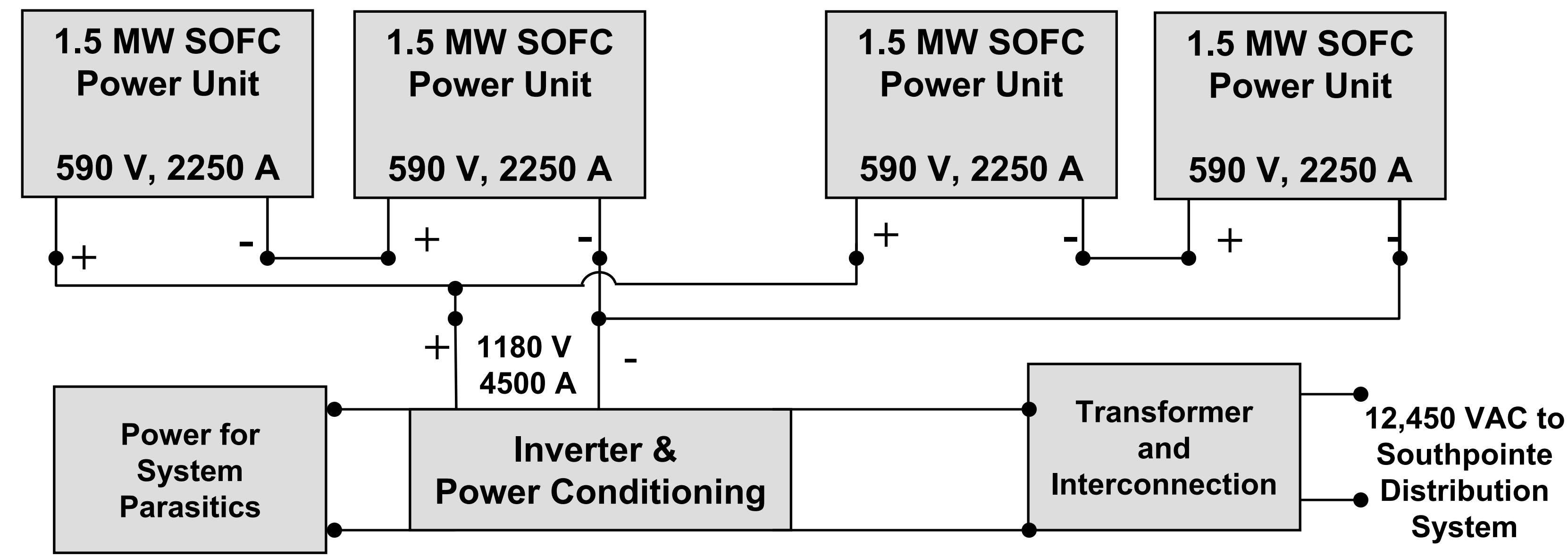


The small, medium, and large office buildings each have similar load profiles on an energy intensity basis.



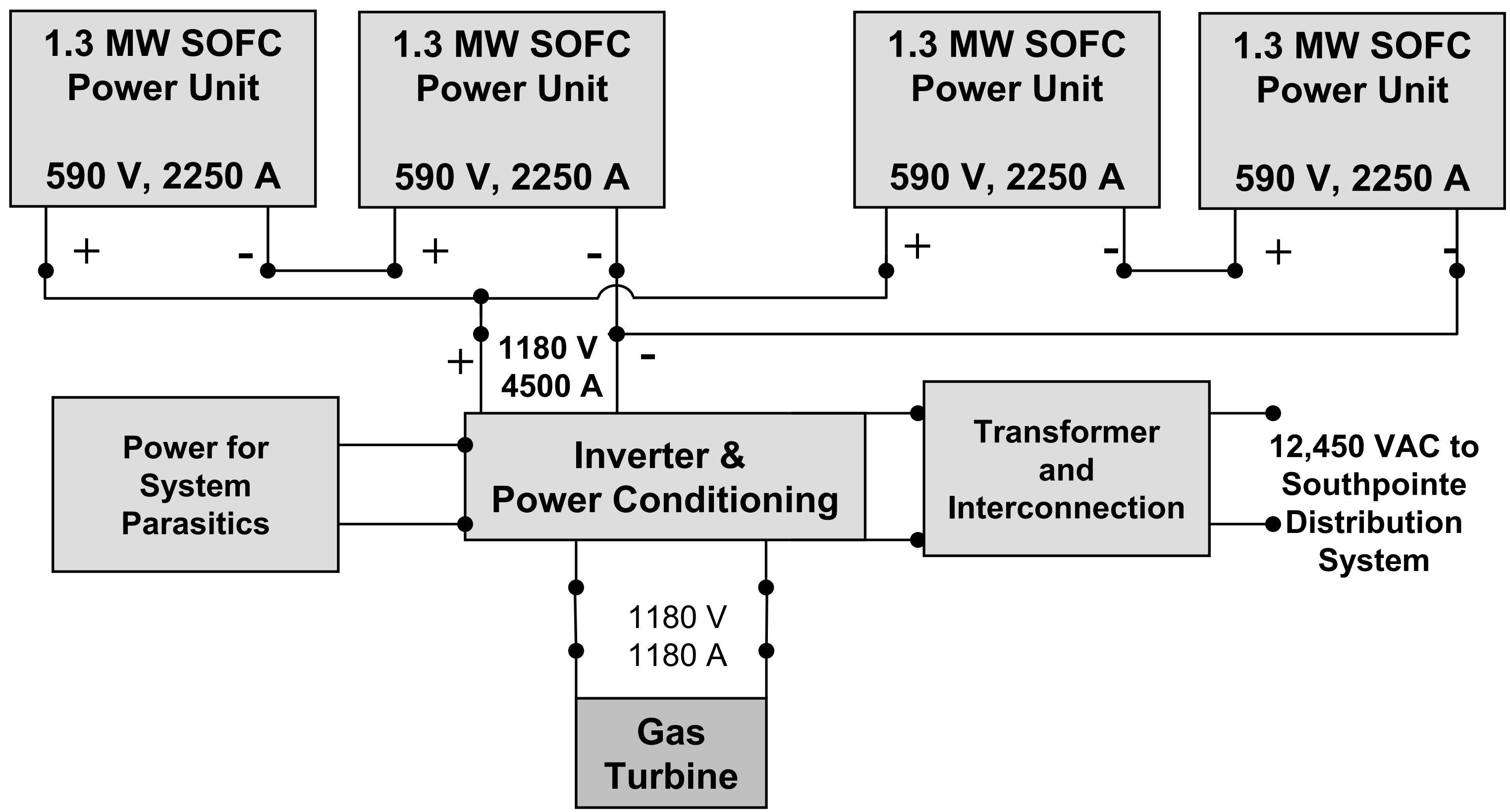
The Simple-Cycle plant uses four SOFC power modules, power conditioning, and a transformer to provide power at the distribution system voltage.

Electrical Connections



The hybrid plant uses four SOFC power modules, a gas turbine, power conditioning, and a transformer to provide power at the distribution system voltage.

Electrical Connections



We developed manufactured-cost estimates based on previous SECA analyses.

- Manufactured costs based on recent SECA 1.3 MW Hybrid Plant Study[1]
- Manufactured cost per unit capacity ($/kW) is relatively constant per the range of interest (1 MW to 10 MW)
- Manufactured-cost estimates do not include distribution chain mark-up and, hence, are lower than installed costs.

These estimates are provided for informational purposes, but not used in calculations.

[1]Scale-Up of Planar SOFC Stack Technology for MW-Level Combined Cycle System, TIAX LLC; Reference DO136; October 2003.

Top-level cost estimates show that the factory cost for a simple-cycle SOFC plant is about $280/kWe[1].

	Cost for 6MW Plant[2]	Cost per kW System Rated Capacity[2]
SOFC Power Module Total	**$984,000**	**$164**
SOFC Stacks	$672,000	$112
Vessel	$66,000	$11
Vessel Insulation	$48,000	$8
Manifolding	$113,200	$19
Assembly	$85,800	$14
BOP Total	**$682,000**	**$113**
Power Conditioning	$310,000	$52
Instrumentation and Controls	$186,200	$31
Piping and valves	$186,200	$31
System Factory Cost	**$1,666,000**	**$278**

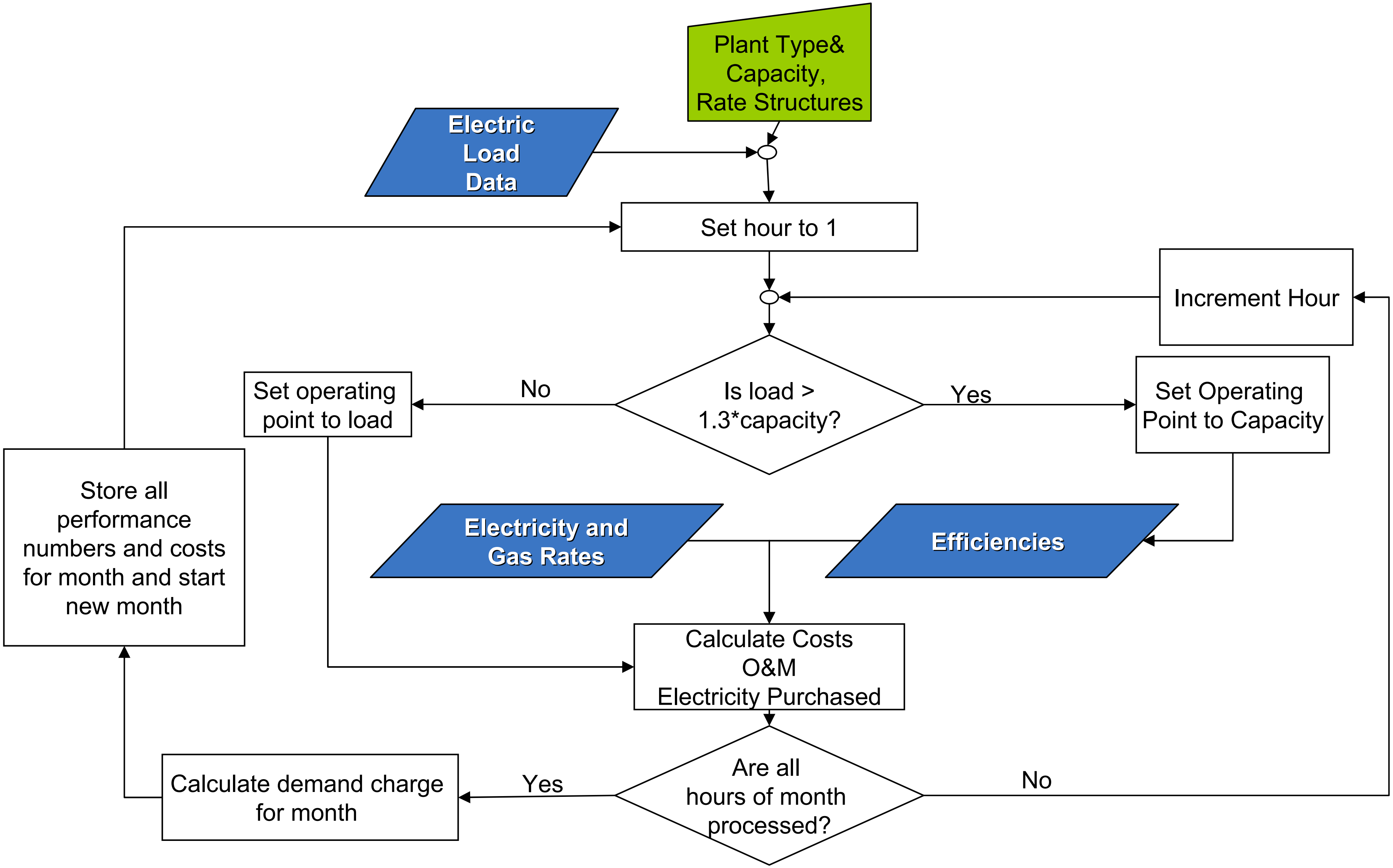
[1]Adapted from Scale-Up of Planar SOFC Stack Technology for MW-Level Combined Cycle System; TIAX LLC; Ref. D0136; October 2003. Omitted Gas Turbine costs, but retained all other balance-of-plant costs. Cost per kW now based on reduced generation capacity of simple-cycle plant.

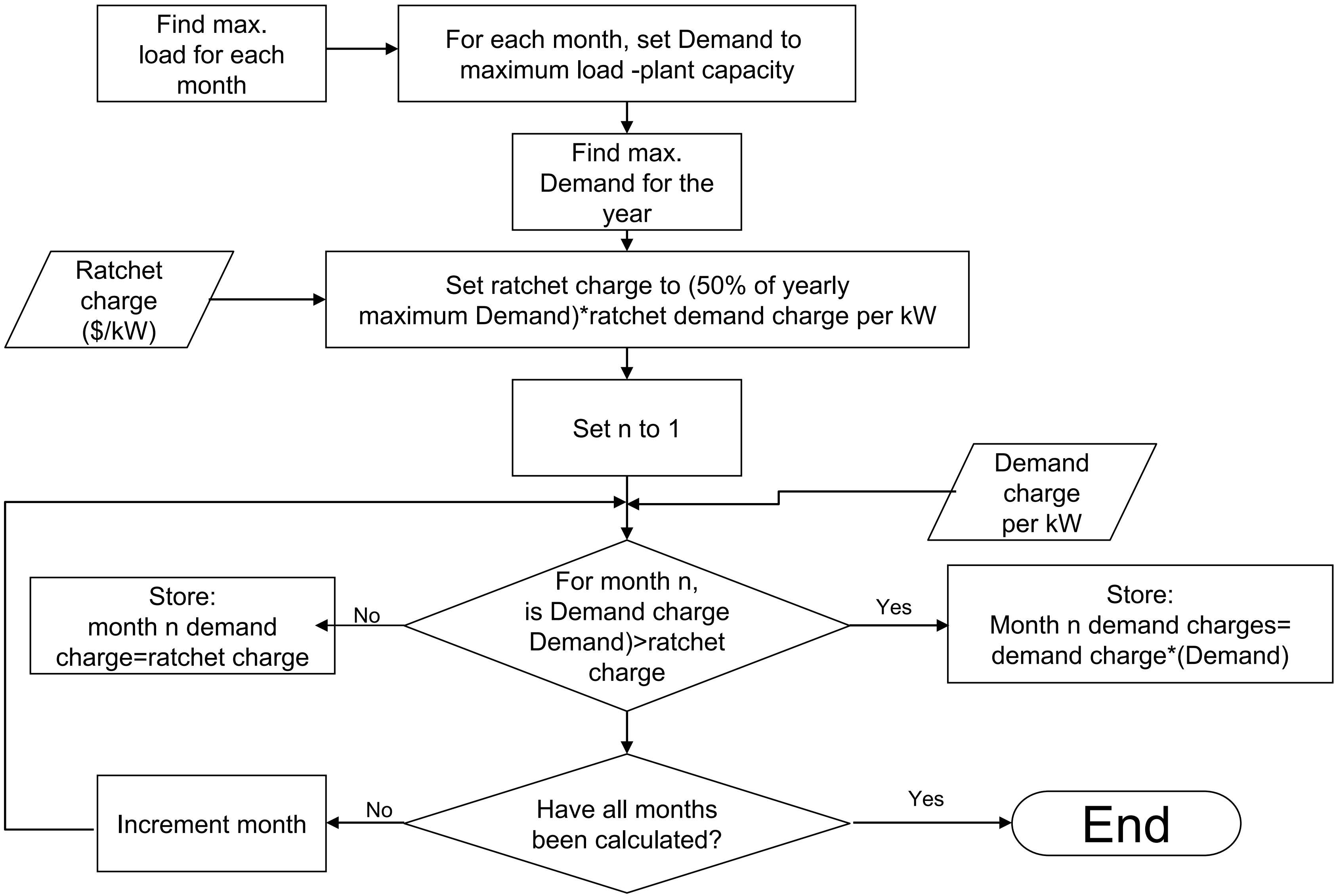
[2]Assumed manufacturing volume of 100 units/year for costing purposes, equivalent to stack manufacturing volume of 250 MW/yr, which is consistent with previous cost estimates for stack manufacturing costs.

Top-Level cost estimates show that the factory cost for the SOFC-Gas Turbine Hybrid System is about $430/kWe.[1]

	Cost for 6MW Plant[2]	Cost per kW System Rated Capacity[2]
SOFC Power Module Total	**$822,000**	**$137**
SOFC Stacks	$564,000	$94
Vessel	$54,000	$9
Vessel Insulation	$36,000	$6
Manifolding	$96,000	$16
Assembly	$72,000	$12
BOP Total	**$1,740,000**	**$290**
Gas Turbine	$880,000	$148
Recuperators	$192,000	$32
Power Conditioning	$300,000	$50
Instrumentation and Controls	$180,000	$30
Piping and Valves	$180,000	$30
System Factory Cost	**$2,562,000**	**$427**

[1]From Scale-Up of Planar SOFC Stack Technology for MW-Level Combined Cycle System; TIAX LLC; Ref. D0136; October 2003.
[2]Assumed manufacturing volume of 100 units/year for costing purposes, equivalent to stack manufacturing volume of 250 MW/yr, which is consistent with previous cost estimates for stack manufacturing costs.


Plant Type&
Capacity,
Rate Structures
Electric
Load
Data
Set hour to 1
Increment Hour
Is load >
1.3*capacity?
No
Yes
Set operating
point to load
Set Operating
Point to Capacity
Store all
performance
numbers and costs
for month and start
new month
Electricity and
Gas Rates
Efficiencies
Calculate Costs
O&M
Electricity Purchased
Are all
hours of month
processed?
Yes
No
Calculate demand charge
for month


Find max. load for each month
For each month, set Demand to maximum load -plant capacity
Find max. Demand for the year
Ratchet charge ($/kW)
Set ratchet charge to (50% of yearly maximum Demand)*ratchet demand charge per kW
Set n to 1
Demand charge per kW
For month n, is Demand charge Demand)>ratchet charge
No
Store: month n demand charge=ratchet charge
Yes
Store: Month n demand charges= demand charge*(Demand)
Have all months been calculated?
No
Increment month
Yes
End

There are several plausible business models for DG operation at Southpointe.

Largely transparent to end user	◆ Allegheny Power (the local utility) owns and operates DG ◆ Third party owns and operates DG, and sells to Allegheny
End user has two suppliers	◆ Third party owns and operates DG, and sells to end users
End user has one supplier	◆ Southpointe owns and operates DG, purchases additional electricity from Allegheny at a negotiable rate, and sells to end users

We established gas rates appropriate for the DG system operation based on discussions with Columbia Gas (one of the gas companies servicing Southpointe).

- Commodity charge: $6.00/Mcf (from NYMEX pricing + fee)[1]
- Distribution charge: $0.63/Mcf (Columbia LDS pricing between 100,000 - 300,000 MCF annually)[2]
- Customer Charge: $1620 per month[2]

[1]Estimate based on average natural gas pricing during the last twelve months.
[2]Columbia Gas of Pennsylvania, rate structure “LDS”

Allegheny Power rates (as simplified for analysis). Allegheny Power serves Southpointe.

Simplified from Allegheny Power Schedule 30 (Large Office Building)

	Distribution	Transmission	Intangible Transition	Generation	Total
Energy ($/kWh)	$0.007	$0.0035	$0.005	$0.025	$0.0405
Demand[1] ($/kW)	$0.90	$0.50	$0.70	$3.70	$5.86

[1]Schedule 30 includes a ratchet rate for demand: Minimum demand charges are 50% of maximum demand over previous 12 months at $6.99 per kW. The ratchet rate is included in our analysis, with the basis being the maximum demand over the 12 months studied.

We established estimated gas rates appropriate for Chicago and Los Angeles.

- Chicago[1]

  Distribution and transmission: $0.73/MMBtu

  Procurement charge: used monthly charges for twelve month period 1/03-12/03: varied between $5.13/MMBtu and $7.28/MMBtu

- Los Angeles[2]

  Distribution and transmission charge: $1.96/MMBtu

  Procurement charge: used monthly charges for twelve-month period 3/03-2/04: varies between $4.40/MMBtu and $6.70/MMBtu

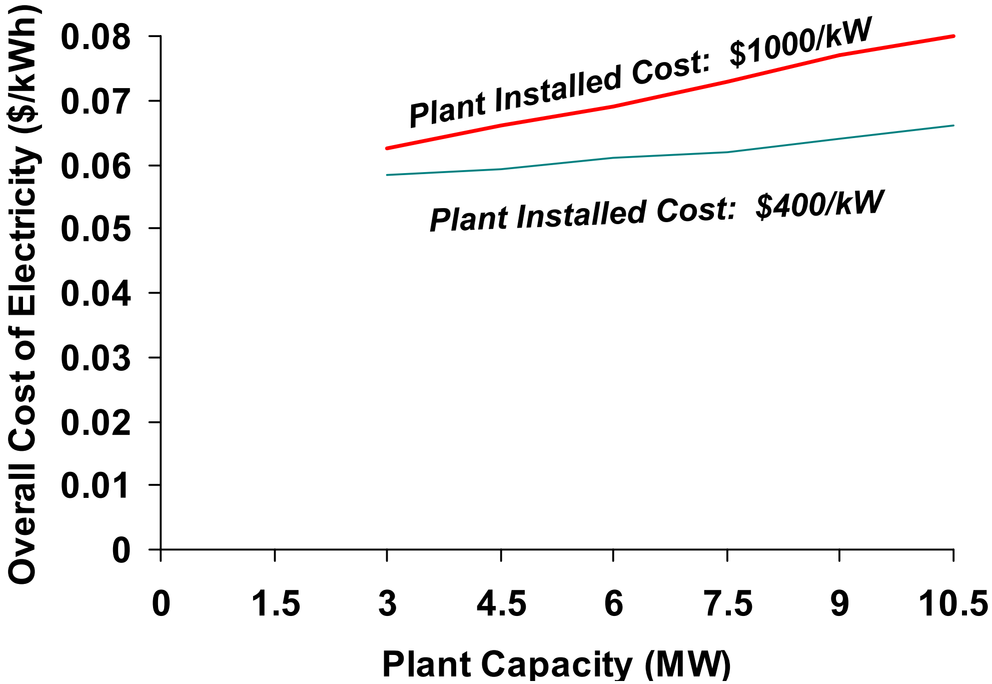
[1]Simplified from The Peoples Gas Light and Coke Company, History of Gas Charges, General Service, Rider 2
[2]Simplified from Southern California gas Company, Tariff Schedule G-CP (Core-Procurement Service)

We established simplified electricity rates for Chicago and Los Angeles.

		Chicago[1]	Los Angeles[2]
Energy Winter	On Peak	$0.056/kWh	$0.30/kWh
	Off Peak	$0.023/kWh	$0.054/kWh
Energy Summer	On Peak	$0.056/kWh	$0.20/kWh
	Off Peak	$0.023/kWh	$0.040/kWh
Demand	Winter	$11.13/kW	$5.40/kW
	Summer	$14.24/kW	$13.15/kW

[1]Simplified from Commonwealth Edison, Rate 6, Time of Use
[2]Simplified from Southern California Edison, Schedule TOU-GS2-SPP-1

A simplified analysis confirms that plant capacity has modest impacts on Overall COE for the simple-cycle plant.

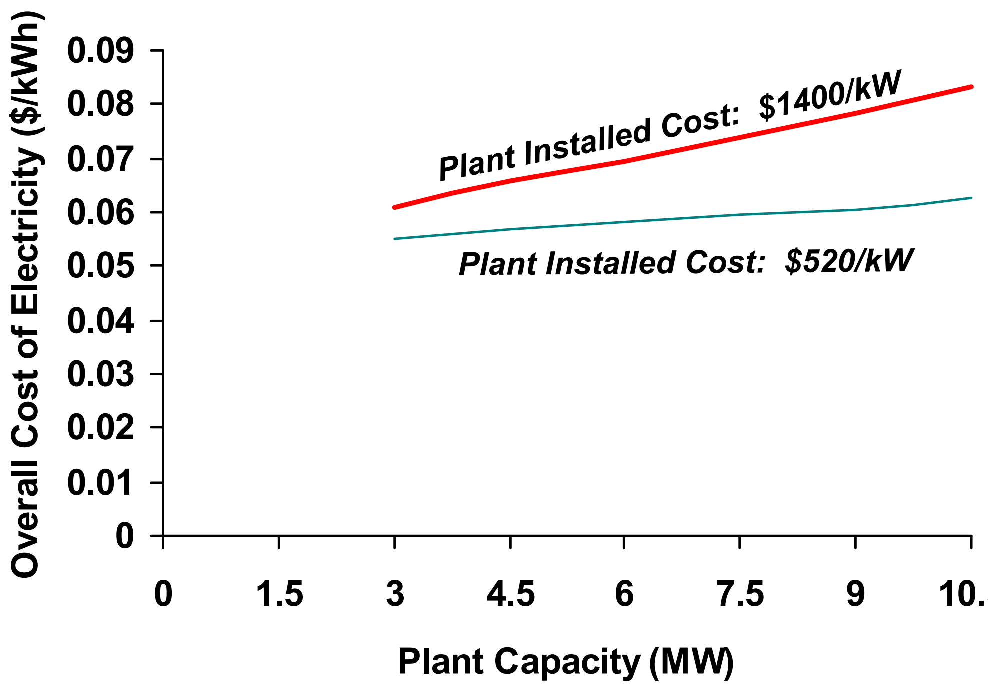


- $0.055/kWh value of electricity
- $6.63/MMBtu gas cost
- $0.01/kWh non-fuel O&M
- Grid electricity purchased only when DG plant cannot meet load (base loaded)
- 54% (LHV) net electric generation efficiency (fixed)
- No operation above rated capacity
- 0.1 Capital Recovery Factor

Plant Capacity (MW)	3	4.5	6	7.5	9	10.5
Capacity Factor	0.98	0.87	0.75	0.64	0.55	0.48
Fraction of Load Generated[1]	0.58	0.77	0.88	0.95	0.98	1.00

1) Fraction of community electric load generated by DG plant.

A simplified analysis confirms that plant capacity has modest impacts on Overall COE for the hybrid plant as well.

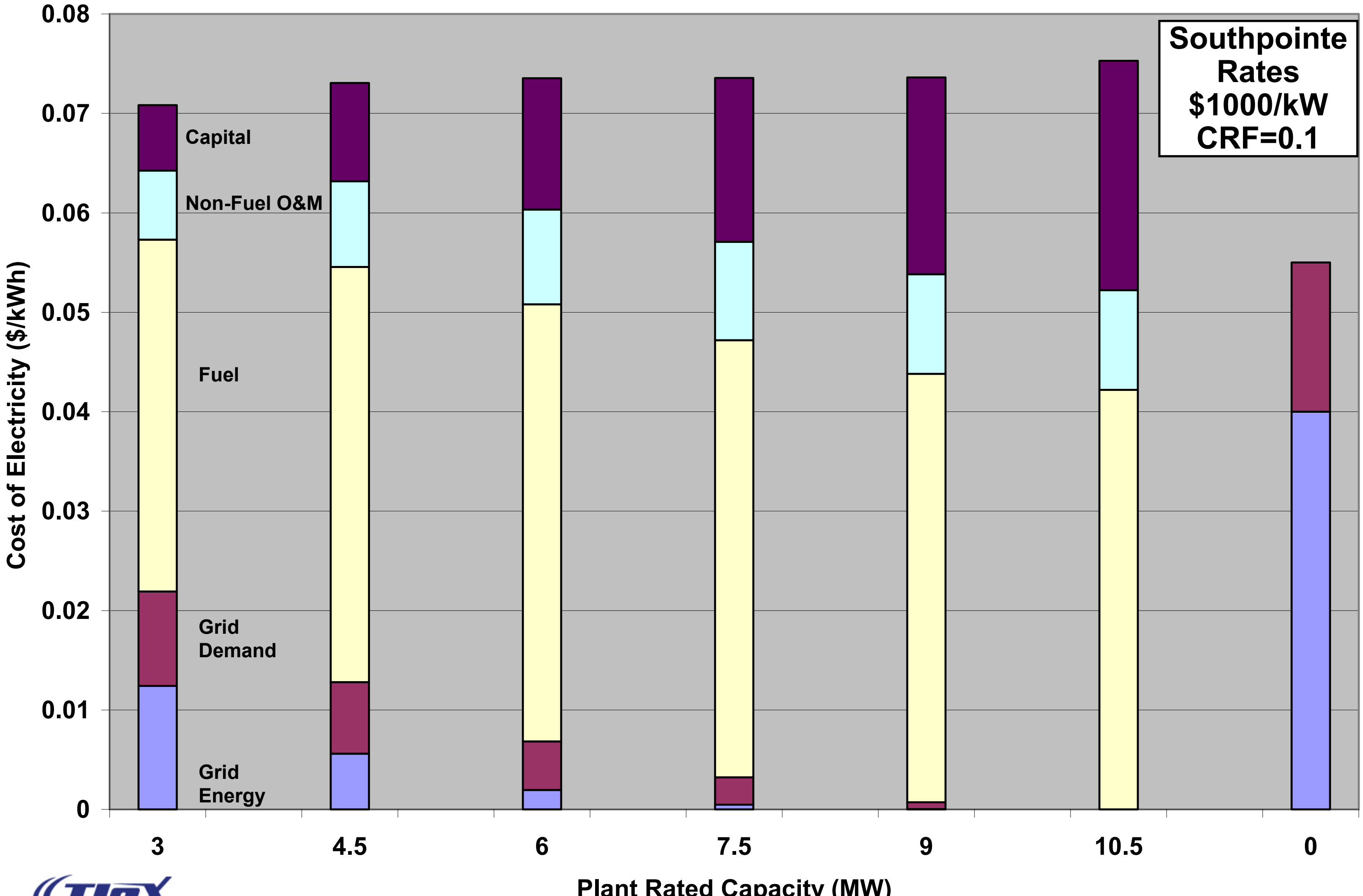


- $0.055/kWh value of electricity
- $6.63/MMBtu gas cost
- $0.0125/kWh non-fuel O&M
- Grid electricity purchased only when DG plant cannot meet load (base loaded)
- 66% (LHV) net electric generation efficiency (fixed)
- No operation above rated capacity
- 0.1 Capital Recovery Factor

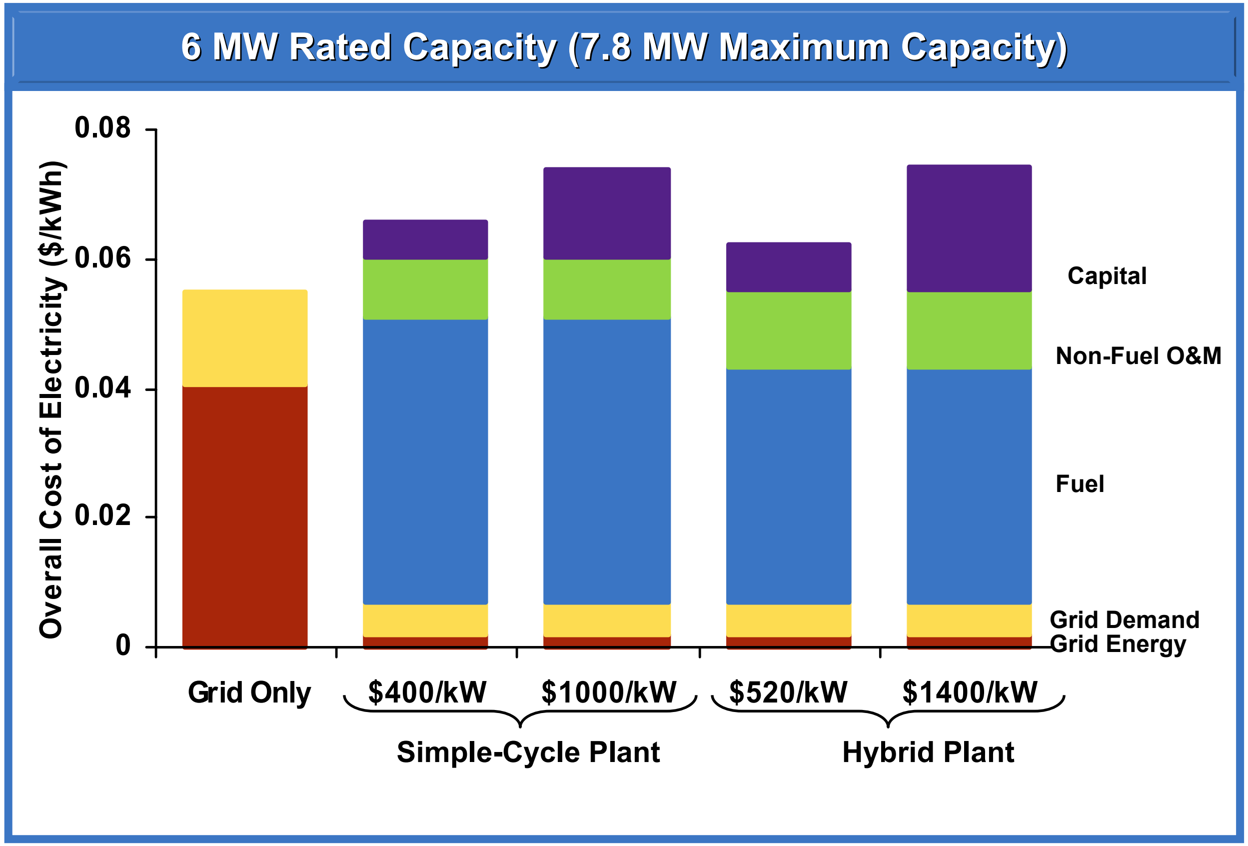
Plant Capacity (MW)	3	4.5	6	7.5	9	10.5
Capacity Factor	0.98	0.87	0.75	0.64	0.55	0.48
Fraction of Load Generated[1]	0.58	0.77	0.88	0.95	0.98	1.00

1) Fraction of community electric load generated by DG plant.

COE is relatively insensitive to plant capacity because grid electricity savings offset capital-cost increases as plant capacity increases.

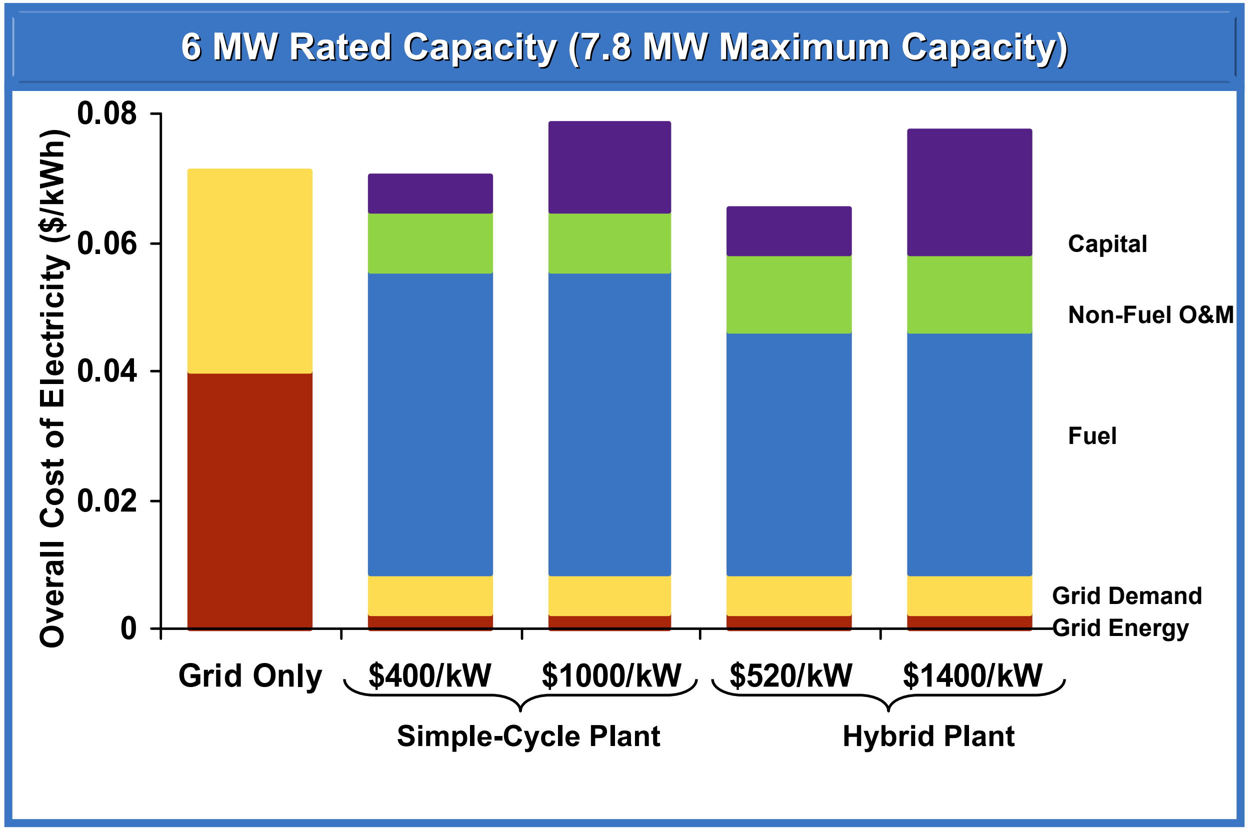


Southpointe electric rates are very low, and benefits beyond end-user economics must be considered to justify SOFC plant installation.



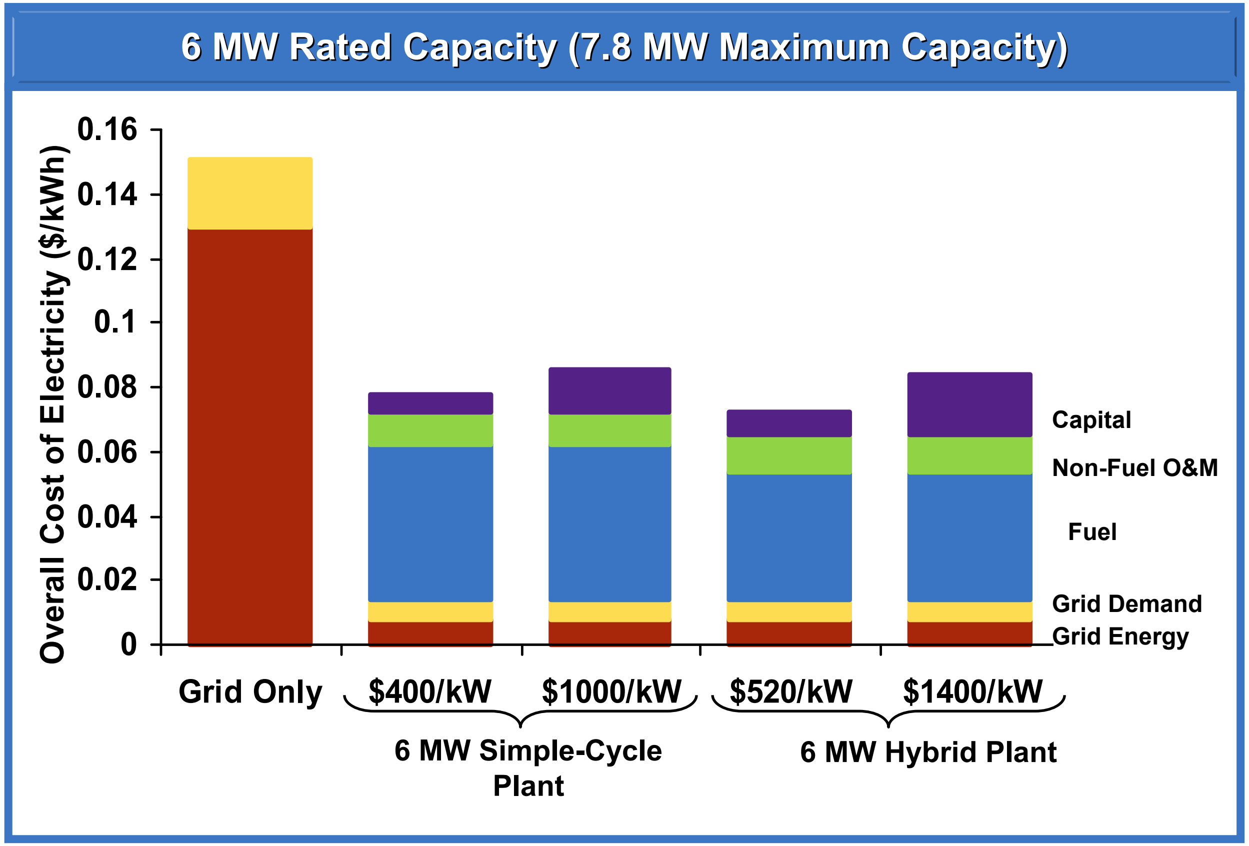
- Allegheny Power Rates for Large office
  - $0.0405/kWh
  - $5.86/kW
  - Rachet demand
- Columbia Gas Rates for DG
  - $6.63/MMBtu
- Operation up to 30% over rated capacity
- Generation efficiency varies with load
- $0.01/kWh non-fuel O&M Simple Cycle
- $0.0125/kWh non-fuel O&M Hybrid Cycle

With Chicago rates, the SOFC plants are competitive based on end-user economics alone at the lower end of installed-cost range considered.



- Rates for Large office
  - $0.023-$0.056/kWh
  - $11.13-$14.24/kW
  - Ratchet demand
- Rates for DG
  - $5.87-$8.01/MMBtu
- Operation up to 30% over rated capacity
- Generation efficiency varies with load
- $0.01/kWh non-fuel O&M Simple Cycle
- $0.0125/kWh non-fuel O&M Hybrid Cycle

With LA rates, the SOFC plants are very competitive based on end-user economics alone across the installed-cost range considered.



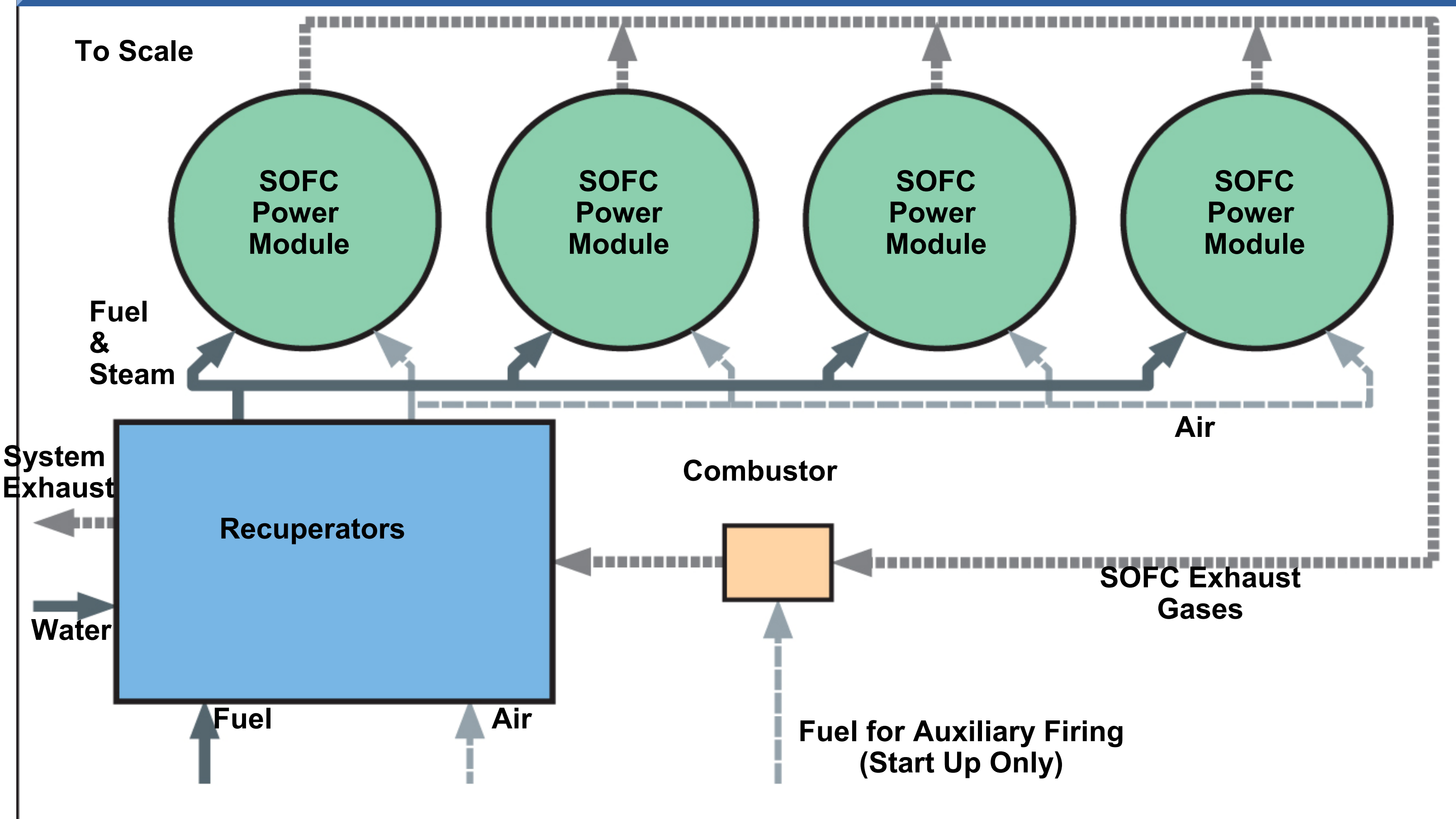
- Rates for Large office
  - $0.043-$0.318/kWh
  - $5.40-$13.15/kW
  - Rachet demand
- Rates for DG
  - $6.41-$8.67/MMBtu
- Operation up to 30% over rated capacity
- Generation efficiency varies with load
- $0.01/kWh non-fuel O&M Simple Cycle
- $0.0125/kWh non-fuel O&M Hybrid Cycle

We identified positive/negative issues related to either technology being sited in communities (in general).

- Space Requirements
- System Architecture
- Noise/Visual Impact/Safety

The installed Simple-Cycle system might occupy roughly 150 m² (1600 sq. feet).

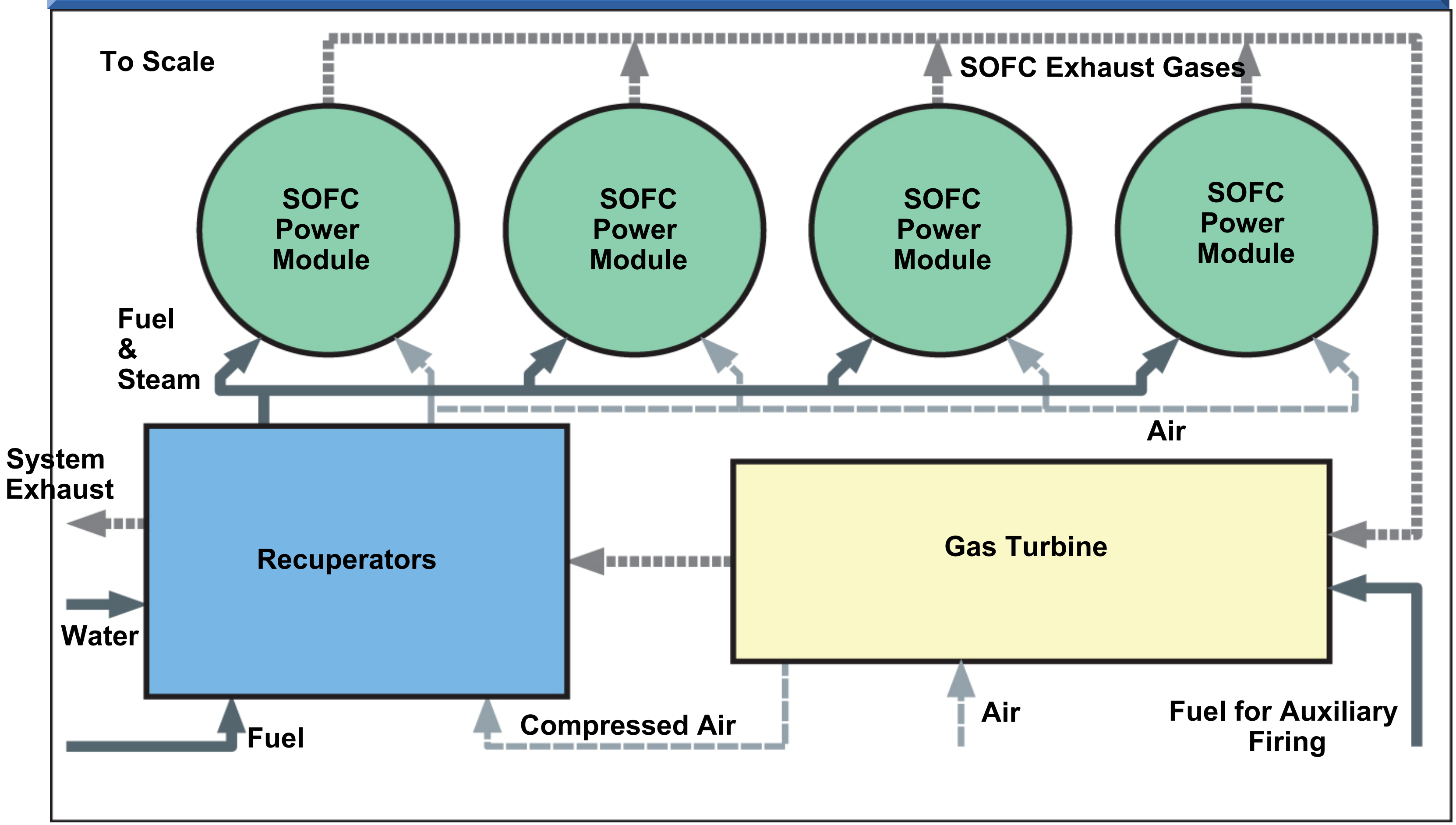
System Layout[1]



1) Power conditioning, transformer, and interconnection equipment not shown

The installed hybrid system might occupy roughly 150 m² (1600 sq. feet).

System Layout[1]



1) Power conditioning, transformer, and interconnection equipment not shown

Noise, visual impacts, and safety should all be within acceptable limits.

- Noise: Primary noise source is the gas turbine of the hybrid plant. Turbine noise is typically 67-92 dB @ 10 feet[1].
- Visual Impact: Condensation of exhaust gas may produce visible plume on some winter days.
- Safety: High Voltages, presence of natural gas, and vessels at 3 atmospheres pressure (hybrid plant).

[1]Range for industrial turbines. From "Fuel Cells, The Future is Here"; John Cassidy, UTC; presented at the Ohio Fuel Cell Coalition, Second Annual Ohio Fuel Cell Symposium, October 4, 2002.

We estimated the exhaust-stream characteristics for heat recovery.

Parameter	6 MW Simple Cycle	6 MW Hybrid Cycle	Remarks
Efficiency	54% LHV 49% HHV	66% LHV 60% HHV	◆Efficiency at rated capacity ◆The combined-cycle system was not optimized for efficiency
Exhaust Temperature	269°C	188°C	◆Exhaust temperature entering heat-recovery system, based on operation at rated capacity
Exhaust Flow Rate	10600 kg/MWh	8260 kg/MWh	◆Based on operation at rated capacity
Exhaust Dew-Point Temperature	49°C	50°C	
Minimum Exhaust Temperature After Heat Recovery	60°C	60°C	◆Minimum temperature to which exhaust can be cooled while avoiding condensation on heat-transfer surfaces
Minimum Exhaust Temperature for Cooling Function	82°C	82°C	◆Minimum temperature consistent with driving single-effect absorption
Recoverable Heat for Heating Loads	3.41 MW (11.6 MMBtuh)	1.72 MW (5.87 MMBtuh)	◆Based on operation at rated capacity
Recoverable Heat for Cooling Loads	3.07 MW (10.5 MMBtuh)	1.44 MW (4.91 MMBtuh)	◆Based on operation at rated capacity, single effect

We roughly estimated average summer commercial building cooling loads by comparing to winter electric load profiles.

- Established non-cooling electric consumption profile from average winter day
  - Assumed economizer cooling used to serve winter cooling loads (i.e., no appreciable winter cooling load)
  - Assumed negligible use of electric space heating in commercial buildings
  - Assumed negligible increase in winter electric loads due to lighting, water heating, and other non-HVAC loads
  - Used hourly loads for average winter and average summer days (as supplied by NETL)
- Approximated average summer cooling electric consumption by subtracting non-cooling electric consumption from average summer total electric consumption
  - Hourly Cooling Electric Consumption = Hourly Total Electric Consumption - Hourly Non-Cooling Electric Consumption. Negative values set equal to zero
  - Accounts for compressors/chillers, chilled water pumps, condenser water pumps, cooling towers, and condenser fans, as these components run only for cooling
  - Does not include air-handling-unit (AHU) supply fans, as these operate year round

- Estimated that roughly 90% of cooling electricity consumption (excluding AHU supply fans) is associated with compressors and chillers
  - Based on previous analysis of commercial HVAC equipment for DOE[1]
  - Weighted average for various equipment types, using the following weighting factors:
    - Packaged AC: 50%
    - Water-Cooled Centrifugal Chiller with Central Variable Air Volume: 12.5%
    - Water-Cooled Centrifugal Chiller with Central Constant Air Volume: 12.5%
    - Air-Cooled Reciprocating Chiller with Central Variable Air Volume: 12.5%
    - Air-Cooled Reciprocating Chiller with Central Constant Air Volume: 12.5%
- Estimated 0.8 kW/ton average compressor/chiller consumption
  - 0.6 kW/ton for chillers (TIAX estimate)
  - 1.0 kW/ton for compressors in packaged AC equipment (TIAX estimate for 10 EER, 10-ton unit)
  - Assumed that these design-point estimates apply across all operating conditions
  - Weighted chillers and packaged units equally for overall average
- Calculated hourly cooling load for average summer day
  - Hourly Cooling Load = $(0.90)\left(\frac{\text{ton}}{0.8\ \text{kW}}\right)$ (Hourly Cooling Electric Consumption)

[1]For New York City small office. From Figure 5-6 of "Energy Consumption Characteristics of Commercial Building HVAC Systems Volume I: Chillers, Refrigerant Compressors and Heating Systems"; prepared for DOE/BTS; prepared by Arthur D. Little, Inc.; NTIS No. PB 2001-104340; April 2001.